BIOMECHANICAL ASSESSMENT AND EFFICACY OF THE IMPLEMENTATION OF RUNNING RETRAINING PROGRAMS IN LONG DISTANCE RUNNERS

ALEJANDRO MOLINA MOLINA

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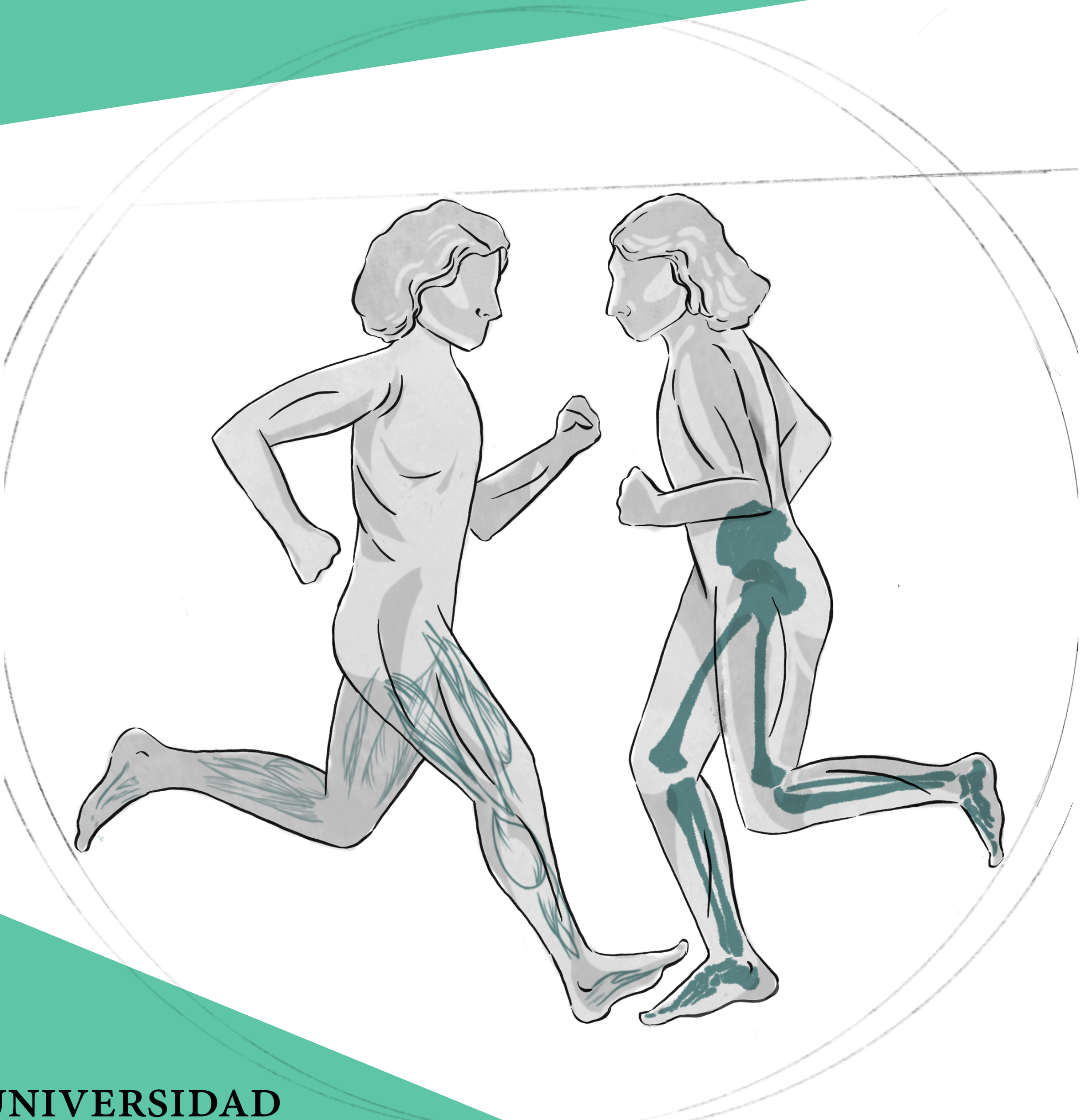

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Valoración biomecánica y eficacia del desarrollo de programas de reeducación técnica en corredores de larga distancia

Biomechanical assessment and efficacy of the implementation of running retraining programs in long distance runners

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“Fix your course to a star and you can navigate through any storm”

Leonardo da Vinci

A mis padres, hermano y pareja

To my parents, brother and partner

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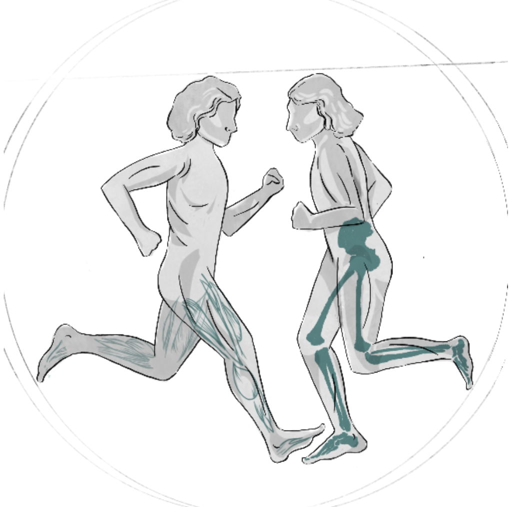

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LIST OF PUBLICATIONS

Peer-reviewed publications

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- Molina-Molina A., Latorre-Román P.Á., Mercado-Palomino E., Delgado-García G., Richards J., Soto-Hermoso V.M. (2022). The effect of two retraining programs, barefoot running vs increasing cadence, on kinematic parameters: A randomized controlled trial. Scandinavian Journal of Medicine & Science in Sports. Mar 9;32(3):533–42. *Published.*
- Molina-Molina A., Delgado-García G., Richards J., Mercado-Palomino E., Soto-Hermoso V.M., Latorre-Román P.Á. (2022). Increasing cadence and running barefoot changes lower limb and trunk sagittal kinematics. *Submitted to Sensors.*
- Molina-Molina A., Soto-Hermoso V.M., Latorre-Román P.Á. (2022). Is dynamic footprint and body balance affected by barefoot running or by the 10% increase in cadence? *Submitted to Gait and Posture.*

Conference communications

- Molina-Molina A., Mercado-Palomino E., Garcia-Delgado G., Latorre-Román P.Á., Soto-Hermoso V.M. (2019). Effect of two different retraining programs on popular long-distance in terms of postural balance. 24th Annual Congress of the European College of Sport Science. Prague (Czech Republic); p. 3–6. *Published in Book of Abstract.*

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LIST OF ABBREVIATIONS

ABBREVIATION	DEFINITION
2D	Two dimensions
3D	Three dimensions
ANCOVA	One-way analysis of covariance
ANOVA	Analysis of variance
BAR	Barefoot group
CAD	Cadence group
CAST	Calibrated anatomical system technique
CI	Confidence interval
CON	Control group
COP	Center of pressure
CS	Comfortable speed
CT	Contact time
DOF	Degrees of freedom
EC	Eyes closed
EO	Eyes open
FFS	Forefoot strike
FSA	Foostrike angle
FSP	Foostrike pattern
FT	Flight time
GPS	Global Positioning System
HIIT	High-intensity intermittent training
HUMAN LAB	Human Motion Analysis Lab
IAAF	International Amateur Athletic Federation, nowadays World Athletics
IMUDS	Instituto Mixto Universitario "DEPORTE y SALUD
INV	Inversion
ISB	International Society of Biomechanics
MFS	Midfoot strike
MS	Medium speed
RFS	Rearfoot strike
SD	Standard deviation
SL	Step length
TC	Tiempo de contacto
TV	Tiempo de vuelo

RESUMEN

Introducción. Correr como actividad para mejorar la salud y el rendimiento personal se ha extendido cada vez más entre la población popular. Este fenómeno popular de correr se debe, entre otros factores, a la satisfacción de las necesidades de salud física y psicológica, el logro de objetivos, las recompensas tangibles, las influencias sociales y la fácil disponibilidad. Sin embargo, hoy en día, los corredores sufren lesiones a un ritmo elevado a pesar de los avances científicos y tecnológicos en torno a la carrera, el control del entrenamiento, la técnica o el calzado. Avanzar en la descripción de las características biomecánicas de estos corredores es necesario en términos de prevención de lesiones y mejora del rendimiento. El tipo de pisada ha sido asociada factores de riesgo de lesiones asociadas a la carrera y la economía de carrera en los corredores de resistencia. Sin embargo, pocos estudios se han llevado a cabo en situaciones reales de competición o sobre grandes masas poblacionales. Además, estudios anteriores han demostrado, por separado, los efectos de correr descalzo y de aumentar la cadencia con resultados similares, como la alteración de los parámetros espaciotemporales, la cinemática de las extremidades inferiores, equilibrio postural y el movimiento del pie al caminar. Sin embargo, existe incertidumbre en la evaluación de estos programas en la misma población de estudio con cargas de entrenamiento similares.

Objetivo general. Analizar indicadores biomecánicos del gesto de locomoción humana corriendo, en condiciones ecológicas (en competición), y su optimización mediante el desarrollo de programas de reeducación de la técnica en corredores de resistencia amateur.

SECCIÓN 1: Biomechanical running assessment in a real competition situation.

ESTUDIO 1. Does fatigue affect the kinematics of endurance running? El objetivo específico fue determinar el patrón de pisada (FSP), la inversión (INV) y las variables espaciotemporales en una amplia muestra de corredores amateurs durante una competición de larga distancia, en función del sexo y de los cambios en la carrera de clasificación. Se analizaron 368 hombres y 67 mujeres que participaron en la XVII Media Maratón Internacional de Córdoba (España). Se grabó en el km 5 y en el km 15, donde se utilizaron cámaras de vídeo de alta velocidad y técnicas de fotogrametría 2D para medir el FSP, el INV, el tiempo de contacto (CT) y el tiempo de vuelo (FT). El grupo que

empeoró su clasificación en el km 15 aumentó la prevalencia del FSP y la asimetría del INV. Un análisis de Pearson indica que la variación de la clasificación en la carrera entre las marcas km 5 y km 15 está relacionada con el TC ($r=0.429$, $p<0.001$) y el FT ($r=-0.360$, $p<0.001$). La prevalencia del RFS y los parámetros espaciotemporales mostraron patrones diferentes en función de si los corredores mejoraban o empeoraban su clasificación.

SECCIÓN 2: Eficacia de dos programas de reeducación de la técnica de carrera para corredores amateurs de larga distancia.

ESTUDIO 2. The effect of two retraining programs, barefoot running versus increasing cadence: a randomised controlled trial. El objetivo específico fue comparar los efectos de dos programas de reducción de la técnica de carrera de 10 semanas de duración, fuera del laboratorio, sobre la cinemática del pie y los parámetros espaciotemporales en corredores amateurs. Ciento tres corredores amateurs (30 ± 7.2 años, 39% mujeres) fueron asignados aleatoriamente a: un grupo de reeducación descalzo (BAR) con 3 sesiones/semana durante 10 semanas, un grupo de reeducación basado en la cadencia (CAD) que volvió a aumentar la cadencia en un 10% con 3 sesiones/semana durante 10 semanas y un grupo de control (CON) que no realizó ninguna reeducación de la técnica. El patrón de pisada, el ángulo de pisada (FSA) y las variables espaciotemporales a velocidades cómodas y altas se midieron utilizando fotogrametría 2D/3D y un sistema de fotocélulas en el suelo. Se utilizó un ANOVA 3x2 para comparar entre los grupos y los 2 puntos temporales. La FSA se redujo significativamente a la velocidad cómoda en 5.81° para BAR ($p < 0.001$; d de Cohen = 0.749) y en 4.81° para CAD ($p = 0.002$; d de Cohen = 0.638), y a alta velocidad en 6.54° para BAR ($p < 0.001$; d de Cohen = 0.753) y en 4.71° para CAD ($p = 0.001$; d de Cohen = 0.623). La cadencia aumentó significativamente un 2% en el grupo CAD ($p = 0.015$; d de Cohen = 0.344) a velocidad cómoda y el grupo BAR mostró un aumento del 1.7% a alta velocidad. Los programas de reeducación de la técnica BAR y CAD mostraron un efecto moderado para reducir el FSA y la prevalencia del retropié, y un efecto pequeño para aumentar la cadencia. Ambos ofrecen herramientas de bajo coste y viables para la modificación de la marcha en corredores amateurs en escenarios clínicos.

ESTUDIO 3. Changes in lower limbs and trunk kinematics after two 10-week running retraining programs: increasing cadence versus running barefoot. El objetivo específico fue comparar los efectos de dos programas de reeducación de la técnica de carrera en condiciones ecológicas sobre la cinemática de las extremidades inferiores y el tronco en corredores amateurs a velocidad cómoda y a alta velocidad. Sesenta y ocho corredores amateurs (30 ± 7,3 años, 38% mujeres) fueron asignados aleatoriamente a un grupo de pies descalzos (BAR), a un grupo de cadencia (CAD) o a un grupo de control (CON). BAR incluía intervalos cortos de carrera descalza mientras que CAD aumentaba la cadencia basal a velocidad cómoda en un 10% Ambos programas de reeducación incluían tres sesiones semanales durante 10 semanas. Se midió la cinemática sagital en 3D del tobillo, la rodilla, la cadera, la pelvis y el tronco antes y después del programa de reeducación, a velocidad cómoda y a alta velocidad. Un ANOVA 3 × 2 reveló que los grupos BAR y CAD aumentaron la flexión de la rodilla en el golpe de pie, disminuyeron la extensión máxima en la fase inicial del swing, aumentaron la flexión de la cadera y la inclinación anterior de la pelvis, a velocidad cómoda y alta después de la reeducación. Además, BAR mostró un aumento de la flexión plantar del tobillo en el footstrike y un aumento de la inclinación anterior del tronco. Se encontraron cambios significativos de tamaño de efecto de moderado a grande para ambos programas de reeducación de carrera, lo que demuestra una familiarización motora similar utilizando herramientas clínicamente poco sofisticadas que podrían reducir los riesgos mecánicos de lesión asociados a una tensión excesiva de la rodilla. Los cambios hallados a velocidad cómoda (velocidad objetivo de la intervención) también se encontraron a alta velocidad, lo que podría provocar cambios en el rendimiento en carrera.

ESTUDIO 4. Effects of barefoot running vs increasing cadence retraining programs, on body balance and dynamic foot motion. El propósito del presente estudio es determinar el efecto de dos programas diferentes de reeducación de la técnica de carrera (periodos de carrera descalza y aumento del 10% de la cadencia basal) sobre el equilibrio corporal y el movimiento dinámico del pie en corredores amateurs. Se trata de un ensayo controlado no aleatorizado. Setenta y dos corredores de resistencia (30.0 ± 7.1 años, 43% mujeres) fueron asignados a un grupo de carrera descalza (BAR) (n = 23), a un grupo de aumento del 10% de la cadencia (CAD) (n = 24), ambos con 3 sesiones/semana durante 10 semanas, y a un grupo de control (CON) (n = 25) que no realizó ningún programa de reeducación. El equilibrio corporal (es decir, el área del centro de presión [COP], la longitud y la velocidad) y los parámetros de presión plantar de la dinámica de la marcha (es decir, la superficie y las áreas por zonas plantares, el tiempo de contacto y la duración de las fases de balancín en la marcha) se midieron con una plataforma de presión plantar antes y después de la intervención. Las pruebas de equilibrio postural fueron equilibrio bipodal (ojos abiertos [OA] y ojos cerrados [OC]), equilibrio monopodal sobre la pierna dominante (OA y OC) y sobre la pierna no dominante (OA y OC). Se utilizó ANCOVA para probar las diferencias entre los grupos BAR, CAD y CON después de la intervención, ajustando los valores previos a la intervención. El grupo CAD mantuvo sus parámetros basales de equilibrio corporal, mientras que BAR redujo la longitud y la velocidad de la COP (diferencia media de los grupos -144.05 mm y -10.80 mm/s, respectivamente) para la pierna no dominante con OC. El grupo CON mantuvo sus parámetros de equilibrio corporal de referencia, mientras que BAR redujo el área, la longitud y la velocidad del COP (diferencia media de los grupos -1227.01 mm2, -207.00 mm y -16.78 mm/s, respectivamente) para la pierna no dominante con OC. El uso parcial de la carrera descalza en el programa de entrenamiento de corredores amateurs de 3 sesiones semanales con un aumento progresivo de los minutos produjo mejoras en el equilibrio corporal.

Conclusiones. SECCIÓN 1: Los resultados de la presente sección sugieren que mantener un apoyo adelantado, no aumentar el tiempo de contacto y no disminuir el tiempo de vuelo podría ser beneficioso para mejorar el rendimiento durante una carrera de larga distancia en los últimos kilómetros. **SECCIÓN 2:** Tras 10 semanas de los programas de reeducación de carrera basada en periodos de carrera descalza y aumento de un 10% de la cadencia basal se observaron cambios compartidos (disminución ángulo del pie en el contacto inicial, aumento de la flexión de rodilla, cadera y mayor inclinación anterior de pelvis). Aunque hay que destacar que el programa de periodos de carrera descalza mostró cambios (reducción de la prevalencia de apoyos retrasados, disminución de la longitud de paso, reducción del ángulo de flexión dorsal de tobillo en el contacto inicial, aumento la inclinación anterior de tronco y cambios en el equilibrio postural), que por el contrario el aumento de cadencia de un 10% no mostró.

ABSTRACT

Introduction. Running as an activity to improve health and personal performance has become increasingly widespread among the popular population. This popular phenomenon of running is due to, among other factors, the satisfaction of physical and psychological health needs, the achievement of goals, tangible rewards, social influences and easy availability. However, today, runners suffer injuries at a high rate despite scientific and technological advances in running, training control, technique and footwear. Progress in describing the biomechanical characteristics of these runners is necessary in terms of injury prevention and performance improvement. Footstrike pattern has been associated with risk factors for running injuries and running economy in endurance runners. However, few studies have been carried out in real competition situations or on mass populations. In addition, previous studies have demonstrated, separately, the effects of barefoot running and increasing cadence with similar results, such as the alteration of spatiotemporal parameters, lower limb kinematics, postural balance and walking foot motion. However, there is uncertainty in the evaluation of these programmes in the same study population with similar training loads.

General aim. To analyse biomechanical indicators of human running locomotion, under natural and non-invasive conditions (in competition), and its optimisation through the implementation of running retraining programs in recreational endurance runners.

SECTION 1: Biomechanical running assessment in a real competition situation.

STUDY 1. Does fatigue affect the kinematics of endurance running? The specific aim was to determine the footstrike pattern (FSP), inversion (INV) and spatial-temporal variables in a large sample of recreational runners during a long-distance competition, according to sex and changes in the classification race. A total of 368 men and 67 women, who participated in the XVII International Half Marathon of Cordoba (Spain) were analysed. It was recorded at km 5 and km 15, where high-speed camcorder and 2D-photogrammetric techniques were used to measure FSP, INV, contact time (CT) and flight time (FT). The group that worsened their classification at km 15 increase RFS prevalence and INV asymmetry. A Pearson analysis indicates that variation of the classification in the race between the marks km 5 and km 15 is related with CT ($r=0.429$, $p<0.001$) and FT ($r=-0.360$, $p<0.001$). RFS prevalence and spatial-temporal parameters

showed different patterns depending on whether the runners improved or worsened their ranking.

SECTION 2: Effectiveness of two running retraining programs for recreational long-distance runners.

STUDY 2. The effect of two retraining programs, barefoot running versus increasing cadence: a randomised controlled trial. The specific aim was to compare the effects of two 10-week non-laboratory based running retraining programs on foot kinematics and spatiotemporal parameters in recreational runners. One hundred and three recreational runners (30 ± 7.2 years old, 39% females) were randomly assigned to either: a barefoot retraining group (BAR) with 3 sessions/week over 10 weeks, a cadence retraining group (CAD) who increased cadence by 10% again with 3 sessions/week over 10 weeks and a control group (CON) who did not perform any retraining. The footstrike pattern, footstrike angle (FSA) and spatial-temporal variables at comfortable and high speeds were measured using 2D/3D photogrammetry and a floor-based photocell system. A 3x2 ANOVA was used to compare between the groups and 2 time points. The FSA significantly reduced at the comfortable speed by 5.81° for BAR ($p < 0.001$; Cohen's $d = 0.749$) and 4.81° for CAD ($p = 0.002$; Cohen's $d = 0.638$), and at high speed by 6.54° for BAR ($p < 0.001$; Cohen's $d = 0.753$) and by 4.71° for CAD ($p = 0.001$; Cohen's $d = 0.623$). The cadence significantly increased by 2% in the CAD group ($p = 0.015$; Cohen's $d = 0.344$) at comfortable speed and the BAR group showed a 1.7% increase at high speed. BAR and CAD retraining programs showed a moderate effect for reducing FSA and rearfoot prevalence, and a small effect for increasing cadence. Both offer low-cost and feasible tools for gait modification within recreational runners in clinical scenarios.

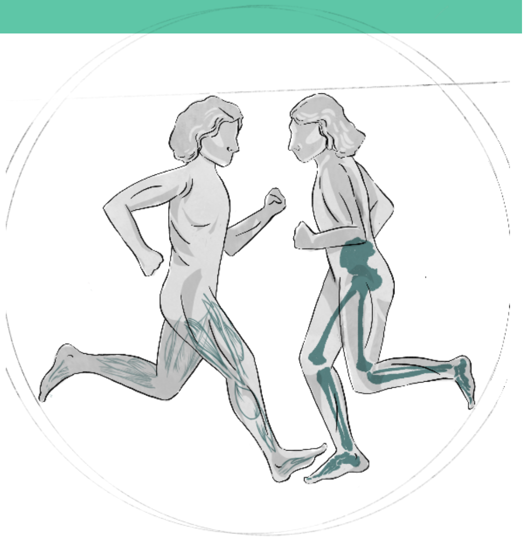
STUDY 3. Changes in lower limbs and trunk kinematics after two 10-week running retraining programs: increasing cadence versus running barefoot. The specific aim was to compare the effects of two non-laboratory based running retraining programs on lower limbs and trunk kinematics in recreational runners at comfortable speed and high speed. Sixty-eight recreational runners (30 ± 7.3 years old, 38% females) were randomly assigned to a barefoot group (BAR), a cadence group (CAD) or a control group (CON). BAR include short intervals of barefoot running while CAD increased baseline cadence at comfortable speed by 10% Both retraining programs included three sessions per week over 10 weeks. 3D sagittal kinematics of the ankle, knee, hip, pelvis and trunk were measured before and after the retraining program, at comfortable speed and high speed. A 3 × 2 ANOVA revealed that the BAR and CAD groups increased knee flexion at footstrike, decreased maximal extension at initial swing phase, increased hip flexion, and increased anterior pelvic tilt, at comfortable and high speed after retraining. In addition, BAR showed increased ankle plantar flexion in the footstrike and increased anterior trunk tilt. Significant moderate to large effect size changes were found for both running retraining programs, demonstrating similar motor familiarisation using clinically unsophisticated tools that could reduce the mechanical risks of injury associated with excessive knee stress. Changes found at comfortable speed (target speed of intervention) were also found at high speed, which could lead to changes in running performance.

STUDY 4. Effects of barefoot running vs increasing cadence retraining programs, on body balance and dynamic foot motion. The specific aim was to determine the effect of two different running retraining programs (periods of barefoot running and 10% increase of baseline cadence) on body balance and dynamic foot motion in recreational runners. This is a non-randomized controlled trial. Seventy-two endurance runners (30.0 ± 7.1 years old, 43% females) were allocated to a barefoot running group (BAR) (n = 23), a 10% increase cadence group (CAD) (n = 24), both with 3 sessions/week over 10 weeks, and a control group (CON) (n = 25) who did not perform any retraining. Body balance (i.e., centre of pressure [COP] area, length and velocity) and dynamics walking plantar pressure parameters (i.e., surface and areas by plantar zones, contact time and duration of rocker phases in gait) were measured with a plantar pressure platform before and after intervention. The postural balance tests were bipodal balance (eyes open [EO] and eyes closed [EC]), monopodal balance on dominant leg (EO and EC) and on non-dominant leg (EO and EC). ANCOVA was used to test differences between the BAR, CAD and CON post-intervention, adjusting for pre-intervention values. CAD group maintained their baseline body balance parameters, while BAR reduced COP length and velocity (mean groups' difference -144.05 mm and -10.80 mm/s, respectively) for non-dominant leg with EC. CON group maintained their baseline body balance parameters, while BAR reduced COP area, length and velocity (mean groups' difference -1227.01 mm2, -207.00 mm and -16.78 mm/s, respectively) for non-dominant leg with EC. A partial use of barefoot running in the recreational runners' training program of 3 sessions per week with a progressive increase in minutes resulted in improvements in body balance.

Conclusions. SECTION 1) The results of the present section suggest that maintaining a forefoot strike, not increasing contact time and not decreasing flight time may be beneficial in improving performance during a long-distance race in the final kilometres. **SECTION 2)** After 10 weeks of the running retraining programs based on barefoot running periods and a 10% increase in baseline cadence, shared changes were observed (decreased foot angle at initial contact, increased knee and hip flexion and greater anterior pelvic tilt). Although it should be noted that the periods of barefoot running program (reduction in the prevalence of rearfoot strikes, decrease in step length, reduction in the angle of dorsiflexion of the ankle at initial contact, increase in anterior trunk tilt and changes in postural balance), whereas the 10% increase in cadence did not.

CHAPTER 1.

INTRODUCTION



1.1. OVERVIEW

HUMAN LOCOMOTION AND RUNNING

Locomotion, defined as the capacity or ability to move from one place to another, has been linked to humans in the form of bipedal locomotion since the earliest evidence of hominids (1,2). This bipedal human locomotion can take two forms. The first is walking, briefly defined as a form of bipedal locomotion in which at least one foot always remains in contact with the ground, alternating a bipodal and monopodal stance, with no flight phase. The second is running, briefly defined as a form of bipedal locomotion in which there is an alternating monopodal right and left leg stance with a flight phase between each monopodal phase. During the flight phase the human being loses contact with the ground (3).

Fossil evidence from at least 4.4 million years ago has linked anthropometric features to the walking ability of early hominids (4). Nevertheless, evidence of adaptations for endurance running in our own homo species seems to appear in the fossil record from 2 million years ago (5). Reasons why early hominids started to run long-distances are not clear. However, several survival-related hypotheses have been proposed. Before the invention of various hunting tools, Homo sapiens had to catch their prey until heat exhaustion (6).

Endurance running has been proposed as a way of helping hunters get close enough to their prey to throw projectiles, to run other mammals to exhaustion in the heat, or perhaps even to compete in scavenging in open, semi-arid environments with other mammals or even other hominids (5). This last hypothesis has been observed in the Hadza in East Africa, who have occasionally used strategies of scavenging meat from carnivores (7).

Lastly, since the first findings of hominid adaptations to endurance running and the hypotheses of the main survival reasons why early hominids could run long distances, there have been enormous socio-demographic changes that drive 21st century humans to run long distances. In contrast, today the popular phenomenon of running is due to, among other factors, to the satisfaction of physical and psychological health needs, the achievement of goals, tangible rewards, social influences and easy availability (8,9).

These new motivations have led, over recent decades, to an enormous increase in popular or recreational long-distance athletic events for recreational or health purposes, both in the number of annual races and in the number of participants who run these races.

THE RISE OF RECREATIONAL RUNNING AS A POPULAR SPORT

From 2009 to 2019, a 10-year period, the recreational running population increased by 57.8%, rising from 5 million participants who completed a popular race in 2009 to 7.9 million participants in 2019, excluding elite runners, walkers, and walks/runs for charity events. In 2016 the peak of participation was reached, with 9.1 million endurance runners crossing the finish line in long-distance races, except in Asia, which is still growing without having reached its peak (10). This data covers 96% of US race results, 91% of race results from the EU, Canada, and Australia and a big portion from Asian, Africa and South America (10).

Furthermore, the races with the highest participations are the 5K distance and half marathon, with participations of 2.9 million and 2.1 million recreational runners respectively in 2018, **Figure 1**. These are followed by the 10K distance and marathon, with participations of 1.8 million and 1.1 million recreational runners respectively in 2018. We should keep in mind that, in 2000, the total participation of popular runners was 1.6-1.8 million. To understand the significant rise of running as a sport of the masses. In addition, approximately only 250-500 thousand recreational runners participated between the 5K, 10K, half marathon and marathon distances, with very similar participation numbers for all distances, **Figure 1** (10).

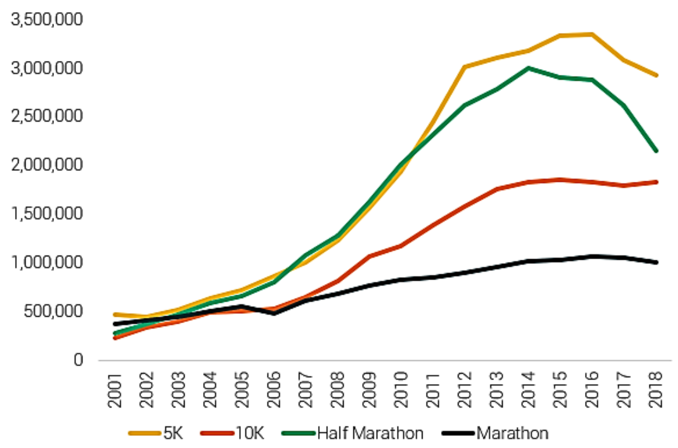


Figure 1. Evolution of participation from 2001 to 2018 by long-distance events according to Andersen et al. (10). Vertical axis; number of persons, and horizontal axis; years.

This rise of popular races has also brought about changes in participation between genders. In the first marathon with the official distance of 42,195 km at the London Olympics at 1908, women were not allowed to run, only men could run the marathon (11). It was not until Los Angeles Olympics in 1984, approximately 99 years later, that women were allowed to run and compete in long-distance races (11). However, since 1984 with the start of men's and women's long-distance races, the proportion of women to men has been increasing to reach 59% women in Iceland, leading the ranking, followed by countries such as the United States with 58% women, and Canada with 57% women. In contrast, there are also countries with much lower ratios, such as Switzerland with 16% female participation or Italy with 19% of women running a marathon (10).

In Europe in particular, the Berlin Marathon held in Berlin, Germany, is a benchmark as a popular sporting event for recreational runners. The number of endurance runners who crossed the finish line in the first edition of the Berlin Marathon in 1974 was only 236 men and 8 women, in contrast to the remarkable increase in 2018 when there was a participation of 28,373 men and 12,268 women (12). Moreover, another characteristic of the evolution undergone during this process of expansion of long-distance events among recreational runners in Europe is that the average times at the end of the half marathon have been getting slower. That is, over time, there are more runners who are slower (12). However, the runners at the top of the Berlin Marathon rankings have also been breaking records and improving their performance (12). In summary, for the Berlin Marathon the evolution has been that more and more recreational runners are slower and more and more professional runners are faster. However, extensive but non-validated double-blind journal research has shown the same trend worldwide, with faster runners being faster and slower runners being slower (10).

In Spain, those who claim to go running at least once a week make up 10% of the general population (13). Moreover, some 5.7 million Spaniards went running at least once a month (13). During the recent edition of the Valencia Half Marathon 2020, a total of 19,076 long-distance runners finished the race. However, although the population of women observed in some countries is proportional to that of men, in this race only 19.51% of the participants were women, showing similar values to those found by Andersen (10) in countries such as Italy or Switzerland.

Finally, in addition to the above-mentioned characteristics, the recreational population running long-distance races is getting older, due to the average age increasing. This characteristic has been observed worldwide (10), but also when looking specifically at long-distance races. For example, for the Berlin Marathon (12), or the international race of San Antón, Jaén, Spain (2011), where around 50% of the runners belonged to the veteran category (around 2000 athletes) (14). Therefore, the average age of participants in popular long-distance races has increased. For the half marathon distance in particular the age is around 40 years old (15).

THE RUNNING CYCLE

The running cycle is composed of a sequence of phases and events of the lower limbs that facilitate the analysis of the runner's technique and biomechanics determined by a succession of movements. To assess the biomechanics of the runner it is necessary to understand the running cycle.

The running cycle begins and ends with the same event, known as the initial foot contact or footstrike. This is the instant when the foot impacts the ground. Two main phases are differentiated during the running cycle: the stance phase and the swing phase. And the footstrike defines the beginning of the stance phase. And the take-off defines the beginning of the swing phase and the flight phase.

The stance phase can be subdivided into 3 phases and 4 events to facilitate the analysis of the different biomechanical events that occur, **Figure 2**. As mentioned above, the cycle starts with the initial contact, and this also coincides with the beginning of the stance phase. After the initial contact the first sub-phase of stance begins, known as the absorption phase, where the body prepares itself to receive the load that will be produced from the impact of the foot against the ground. The next event occurs when the whole foot is in contact with the ground or when the surface of the foot in contact with the ground remains stable (no longer increasing the contact surface), giving way to the mid stance phase. This is the moment when the centre of gravity passes through its lowest point and is the result of the cushioning produced during this first sub-phase. The third event is the take-off of the heel from the ground or the reduction of the surface of the foot in contact with the ground, to start the last sub-phase, the propulsion phase. During the last sub-phase, the centre of gravity rises and accelerates upwards and forwards so that finally the fourth and final event occurs which would be the take-off of the runner's foot from the ground. After the take-off of the foot, the final effect of the force produced during the entire stance is manifested and will lead to the next phase, the flight phase which will initiate the swing of the leg.

The flight phase goes from the take-off of one foot to the contact of the contralateral foot, **Figure 2**. The flight phase represents the launch of a projectile (centre of mass) and the characteristics of that flight are due to the action and reaction forces produced during contact.

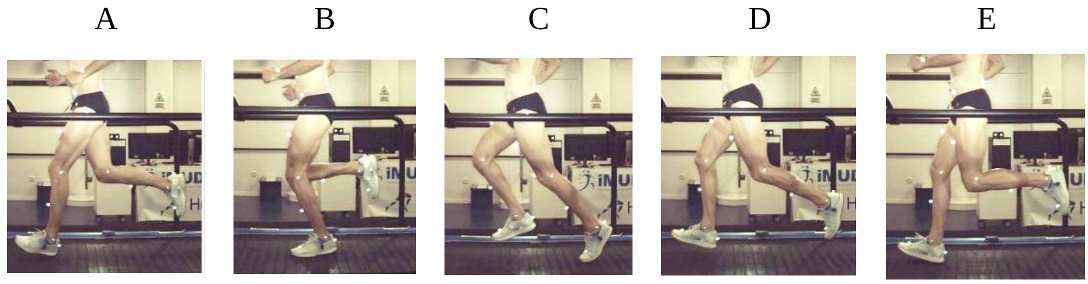


Figure 2. Representation in images of the stance phase and flight phase (one running step). From left to right; A) footstrike left foot; B); mid stance; C) take-off; D) instant of the flight phase; E) footstrike right foot.

The swing phase consists of a repositioning of the leg from the most posterior point at take-off to the most anterior point at landing when initial contact is achieved. The swing phase can be divided into 2 sub-phases. The first is known as the flight phase where the runner is not in contact with the ground. And the second is a contralateral leg contact sub-phase, where the leg we are analysing continues to swing forward at the same time as the opposite leg is in stance phase.

In addition, the ratio of the duration between the contact and swing phase is dependent on the running speed of the runner. During the stance phase, the foot is in contact with the ground and uses the ground reaction forces to generate a propulsive force, allowing the runner to move upwards and forwards. Newton's third law or "action and reaction", in this specific case, explains that when we exert a force on the ground with our foot, it returns a force of the same magnitude and direction, but in the opposite direction. This phenomenon will allow us, by force platforms, to know the reaction forces of the ground and, therefore, the forces that we apply on it. By applying inverse dynamics, we can study the force production phenomena that occur in our body and that allow us to move forward during the race.

Finally, a step is defined as the moment between the contact of one foot to the contact of the contralateral foot, **Figure 2**. Unlike the running cycle that goes from one contact to another contact but of the same foot. Each step, in turn, can be divided into a stance phase and a flight phase. The stance phase goes from the initial contact of the foot with the ground to the take-off of the foot as mentioned above, during the stance phase. Therefore, during the complete running cycle, 2 steps occur.

INCIDENCE OF INJURIES AND THEIR RELATIONSHIP TO RUNNING BIOMECHANICS

While one of the main reasons recreational runners run in the 21st century is to improve their health, the current incidence of injury from long-distance running is remarkably high. Between 26% and 74% of recreational runners have reported a running-related injury during a one-year period according to two recent prospective studies (16,17) and one retrospective study (18). Additionally, after a short observation period of 8 weeks, an injury incidence of 25.9% has been found for running-related injuries in long distance runners (19).

Furthermore, the incidence of running-related injuries is 30.1 per 1000 hours of exposure to running (19). Similarly, a recent meta-analysis has reported that, depending on the type of runner, the definition of the injury, and the duration of follow-up, incidences of running-associated injuries range from 2.5-33 injuries per 1000 hours of running (20). They found that novice runners have a significantly higher risk of injury, 17.8, than recreational runners, who sustained 7.7 running-related injuries per 1000 hours of running (20). In addition, around 25% of long-distance runners are injured at any time of the year, and at least 50% suffer an injury that causes them to stop running for a period of at least one year (21).

Despite scientific advances in sports science such as training load control or running technique, and technological advances such as in the running shoe industry, the incidence of running-related injuries has not changed significantly over the last 20 years as mentioned above. Injuries in endurance runners occur mainly in the lower limbs, with the knee being the most common region with an incidence of injury ranging from 7.2 to 50% (21–23). The knee is followed by the lower leg (9.0% to 32%), the foot (5.7% to 39%) and the upper leg (3.4% to 38.1%) with high incidences (21). The body regions with the least lower extremity injuries in endurance runners were the ankle and hip/pelvis, with incidences ranging from 3.9 to 16.% and 3.3% to 11.5%, respectively for the ankle and hip/pelvis (21), **Figure 3**.

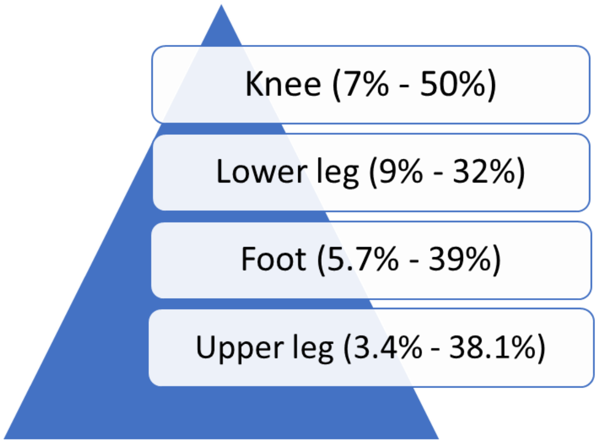


Figure 3. Body regions ordered from highest to lowest injury incidence among recreational runners (from top to bottom). According to Van Gent et al. (21), McKean et al. (23) and Van Mechelen et al. (22).

There are numerous factors that have been associated with the development of injuries in endurance runners. These factors can be classified as either intrinsic or extrinsic. Intrinsic risk factors are those specific to the runner such as age, gender, body composition, genetic component, biomechanical abnormalities, and the existence of previous injury. Extrinsic risk factors are those external to the runner such as temperature, sport discipline, material and equipment (i.e., footwear used), training planning, inadequate warm-up, fatigue, or overtraining (i.e., high mileage) (16,22,24–28).

Recent reviews have associated different intrinsic and extrinsic factors with injury occurrence. For example, runners having a previous injury less than 12 months before has been shown to be a major risk factor for injury, followed by other factors such as errors in training load progression or high mileage in endurance runners (28,29). Similarly, age (23) and BMI (16) have been associated with greater or lesser risk of injury. However, these factors do not explain the different injury locations, for example, whether a runner is more likely to have a knee injury or a foot injury.

In addition, numerous biomechanical parameters have been associated with an increase in running-related injuries (30). To begin with, some spatiotemporal parameters have been individually related to the risk of injury. A low step frequency has been observed as being linked to an increased risk of injury in the shin region (31). A prospective cohort study found that male runners with low or decreased ground contact time suffered more injuries, although this was not associated with any specific body region (32). For the same variable, ground contact time, if we compare the differences between upper limbs, known as bilateral ground contact time asymmetry, it has been observed that the greater the bilateral asymmetry, the greater the risk of suffering a running-related injury (33).

Another category of biomechanical parameters to be considered are those relating to the description of movement, also known as kinematics in the field of biomechanics. Most studies that have sought to relate running-related injuries to running kinematics have focused on the analysis of the lower limbs, i.e. pelvis, hip, knee, ankle and foot (30). Abnormal kinematics for the knee and ankle joint in the sagittal plane at a time during the season without pain or injury has subsequently been associated with Achilles tendon pain. Specifically, an increased knee flexion angle (more extended knee) and an increased ankle dorsiflexion angle, both at the beginning of the stance phase, were observed compared to a group of runners who did not experience pain (34). Also, increased stiffness of the knee during flexion in the sagittal plane has significantly increased the likelihood of sustaining an overuse running injury, especially being more frequent in those runners with higher body weight (over 80 kg body weight), according to a recent 2-year prospective cohort study (35).

In runners with iliotibial band syndrome versus non-injured runners, less hip adduction, and frontal range of motion at the hip joint have been observed. In addition, maximal hip flexion velocity and maximal knee flexion velocity were lower for runners with iliotibial band syndrome. Finally, joint incoordination, expressed as earlier hip flexion and a tendency to earlier knee flexion, proved to be another discriminating variable in subjects with iliotibial band syndrome, compared to uninjured runners (36). Regarding the ankle, it has been observed that a lower ankle eversion range of motion, a lower maximum eversion velocity and a higher maximum eversion angle were present in those cross-country runners who suffered running-related overuse injuries prior to the start of the cross-country season when no runner had any injury or pain (37).

Another category of biomechanical parameters that has been extensively studied for its relationship to running-related injuries is running kinetics, with the study of ground reaction forces. Impact-related variables have been found to be higher for those with medically diagnosed injuries compared to never-injured runners, such as, an increase in vertical (average and instantaneous) loading rate and the vertical impact peak at the beginning of the stance phase (32,38). In particular, when the average vertical loading rate is greater than 66% of body weight, the risk of an overuse running injury is increased (38). This excessive impact loading has been observed for both bone and soft tissue injuries (38).

Furthermore, increased peak impact asymmetry between bilateral steps has been more frequent among injured runners compared to non-injured runners (33). This prevalence of asymmetries for maximal impact has been found to be naturally high for endurance runners (33). Peak braking force alone has been found to be a significant predictor of running-related injury (39). According to a recent study (39), female runners in the highest tercile (with a negative peak braking force greater than 0.27 times body weight) were injured 5.08 times more than those in the middle tercile, and 7.98 times more than those in the lowest tercile. Following a multivariate model analysis, for this study it was the single most influential kinetic variable for injury risk on its own (39). These authors suggested that maximal braking force should be considered as a target parameter to be reduced in running retraining programs (39).

Finally, if we carry out an interpretation connecting some of the aforementioned variables, we can observe that higher cadence and decreased step length are associated with lower peak impact levels of vertical ground reaction force and lower tibial acceleration at impact, in addition to lower sagittal external knee moments and increased sagittal external ankle moment (40–43). Similarly, spatiotemporal variables such as an increase in cadence and decrease in step length have been associated with more flexed knee kinematics at initial impact and less vertical excursion of the foot relative to the centre of mass (40,44,45). The alteration or manipulation of cadence and step length as a running retraining tool has been proposed previously as a useful way to reduce injury risk factors in training or clinical environments. This is due to low-cost requirements and because it can also be carried out in field settings, outside of a laboratory setting (46–50).

However, it should be noted that the identification of biomechanical risk factors for specific running-related injuries does not imply that there is a "perfect" general biomechanical running style applicable to all runners in a clinical or training practice (51). In addition, it is also necessary to understand the relationship between the factors that generate tissue load (external load) and the capacity for tissue regeneration (internal load) in an integrative way, as it has been proposed that there is a capacity for tissue-specific load absorption as well as a capacity for tissue regeneration (52).

RELATIONSHIP BETWEEN BIOMECHANICS AND PERFORMANCE

One of the reasons why so many people nowadays put on their running shoes and go for long distance runs, making endurance running such a popular activity, is to achieve goals, such as beating their personal bests (8,9). To reduce race times during long distance running we need to understand several physiological factors that are determinant for running performance. These physiological determinants of endurance running performance are maximal aerobic capacity, also known as maximal oxygen uptake or VO2max (53,54), lactate threshold (55) and running economy (56).

The maximal oxygen uptake or VO2max is the product of maximal cardiac output and maximal arteriovenous oxygen difference, being considered the best index of aerobic capacity and maximal cardiorespiratory function (53,54). Although the combination of these 3 factors can be modified to improve sporting performance through appropriate training methods, it has been shown that VO2max by itself is not a determinant of running performance. For instance, it was observed that those with the highest VO2max did not always have the best performance, outperforming others at maximal or submaximal paces (56).

Running economy is the rate of oxygen consumed at a given submaximal running speed, also defined as the energy required to run at sub-maximal speed for a given distance (57) and is assessed by measuring the steady-state oxygen consumption at a given running velocity. Hence, running economy has been suggested as a measurement to distinguish runners who can perform better from those with poorer performances. The improvement of running economy has been suggested as a way of increasing running performance in endurance runners (57). There have been suggestions that running economy may vary significantly between endurance runners with similar aerobic capacities (e.g., maximal aerobic capacity or VO2max) leading to the hypothesis that running economy might be the key to endurance running performance (58). According to

Williams and Cavanagh (59), 54% of the variations in running economy can be attributed to biomechanical factors. For instance, the timing and movement of the running stride, the running kinematics and the application of the ground reaction force, for the optimisation of the elastic energy return on the run (60).

These biomechanical determinants of running economy can be classified as either intrinsic to the runner or extrinsic to the runner. Biomechanical factors intrinsic to the runner are those related to the runner's running technique, their running style. According to a recent systematic review of the relationship between running economy and running biomechanics (61), these factors can be broadly classified as spatiotemporal (parameters relating to events and/or phases of the running cycle, such as ground contact time or step frequency); kinematic (parameters for describing movement patterns, such as lower limb joint angles); kinetic (the applied forces responsible for the movement, such as ground reaction force); and neuromuscular (the relationship between the nervous and muscular systems, such as muscle activation or coactivation).

In relation to spatiotemporal parameters, contact time has been an easy-to-measure variable even in a field environment, outside of a laboratory setting (62). However, the findings regarding its relationship to running economy are not entirely clear or conclusive. Some studies have found no relationship (either negative or positive effects) between ground contact time and running economy (59,63–65). Other studies have shown that runners with shorter ground contact time had better levels of running economy (59,65), suggesting that long ground contact times may be metabolically costly because force is produced slowly, meaning that braking phases are longer when runners decelerate (66). Conversely, there are also studies that found that runners with shorter ground contact times had poorer levels of running economy (66,67), suggesting short ground contact times require faster force production and are metabolically costly (68).

The parameters of cadence (defined as steps per minute) and stride length are inversely proportional and are linked to the runner's running speed. On the one hand, if the runner increases the cadence, the stride length will decrease and vice versa. On the other hand, as a runner's running speed increases, cadence also tends to increase and stride length decreases (69,70). The effect of cadence manipulation on biomechanical parameters has been studied, noting that increasing cadence could lead to a reduction in ground reaction force, a reduction in stride length and a reduction in the prevalence of delayed stance (47–50). However, the effects of cadence manipulation on running economy do not seem to be clear. This is probably because no study has assessed its long-term effects. In acute or short-term studies, it has been observed that momentary changes in cadence increasing by 6% are detrimental to running economy (71). However, a recent study observed a decrease in heart rate following an increase in basal cadence in trained endurance runners (72). In the long term the decrease in heart rate could translate into improved running economy in endurance runners, but more research is needed to prove this.

Another variable related to cadence and stride length is vertical oscillation, and its relationship to running economy has been studied. It has been observed that decreasing the vertical oscillation during the running cycle improves running economy (73). The authors suggest that this was probably due to the reduction of vertical oscillation during the stance phase (74). However, this study was carried out on barefoot runners vs. running shoes. Hence, these improvements in running economy could be due to the fact that the reduction in the weight of the shoes reduces the weight that the runner must displace when running, and this reduces running economy, rather than the reduction in vertical oscillation being the responsible parameter. In line with the above, another study found an improvement in running economy after reducing vertical oscillation, but as long as the absolute height of the body's centre of mass remains unchanged (75). In addition, if a runner maintains a low vertical displacement of the centre of mass, the mechanical energy cost is reduced, as the body does less work against gravity (76), which could make running more efficient and thus improve running economy.

According to a recent systematic review and several acute and short effect studies, reducing leg extension at take-off may be beneficial for running economy as a kinematics parameter (59,61,73,77,78). The authors conclude that this could be achieved by less plantar flexion and/or less knee extension at toe-off. Less leg extension at toe-off would reduce the range of posterior flexion required during the flight phase, i.e., during leg swing. By starting in a more flexed position, the moment of inertia of the leg could be reduced, as has been observed in walking (79). This kinematic factor has been hypothesised to improve running economy (61).

The footstrike pattern is another kinematic parameter that has been extensively studied for its relationship to running economy. (60,61,80–82). The use of the different footstrike patterns has been associated to running speed, running surface, fatigue (18) or runners' levels (62). It is noteworthy that among long distance runners, the prevalence of midfoot and forefoot strike is highest among high level runners during a half marathon, being approximately 73% of high level runners (83). Moreover, these runners had lower contact times compared to lower level runners during the race (62,83). As previously mentioned, a shorter contact time with inversion at initial foot contact allows the use of elastic energy and leg muscle stiffness that could increase running economy (84). This has led some researchers to argue that the most economical strike pattern is the forefoot (84,85). However, there is still controversy regarding this variable as there are several studies that found no significant differences for running economy between runners with rearfoot, midfoot or forefoot strike (82,86).

In terms of kinetic factors, the ground reaction forces produced during a runner's stance phase have been proportionally associated with running economy. All three components of ground reaction force separately have been evaluated and associated with improved running economy in endurance runners; a lower vertical impact force (59), a lower medial-lateral force (59), a lower anterior-posterior braking force (63), and also a lower propulsive force for the anterior-posterior component during the propulsive phase (77). In addition, we must pay attention to the alignment of the ground reaction force vector, as an almost perfect alignment of this vector with the vector angle along the longitudinal axis of the leg during the swing phase improved running economy, the authors suggesting that the cause was the reduction of muscle activity during this final phase of the stance (87).

Finally, leg stiffness has been another variable associated with better running economy (88). Stiffness is defined as the ratio of the deformation (vertical displacement) to the applied force (vertical component) and is represented as the whole musculoskeletal system stiffness of the runner (89–91). In a recent acute study, improvements in stiffness and power parameters were observed between the shod and barefoot condition, hypothesising that barefoot running may have benefits for running economy (92), but more research is needed in this regard.

In terms of the association between neuromuscular parameters and running economy, pre-activation of lower limb muscles prior to initial ground contact has been hypothesised to increase muscle-tendon stiffness (66), as muscle-tendon stiffness may enhance muscle force generation during the stretch-shortening cycle (93). For example, an association has been observed between an increase in relative VO2 during prolonged running and a decrease in the ratio of eccentric vs. concentric activity in the quadriceps musculature (94). This increase in the eccentric vs. concentric ratio during the stretch-shortening cycle is due to an increase in muscle activity (concentric phase) during the propulsion phase. Likewise, an increase in lower limb muscle activity (measured by surface electromyography) has been identified as a potential mechanism for increasing VO2 consumption, which could be negatively affecting running economy (63). Therefore, a reduction of muscle activity during the concentric phase of the propulsion phase by muscle pre-activation before the footstrike could improve running economy. (66). In addition, the coactivation of the antagonist-agonist muscles of the musculus, rectus femoris and biceps femoris, that occurs during the loading phase when the knee is flexed, has been shown to be positive for running economy (95).

However, it is necessary to keep in mind that although the mentioned parameters of running biomechanics have shown a strong relationship with running economy, we must approach this knowledge in a cautious and personalised way for each runner. We should not fall into the trap of applying one running technique as "perfect" for all endurance runners. Therefore, more research is needed for the understanding of the individualisation of running biomechanics and running economy in the applied field of clinical or sports training.

THE IMPORTANCE OF FOOTSTRIKE PATTERN

Contrary to an evolutionary perspective where running with forefoot strike seems to be a common feature for early hominids (5,85), more than 90% of recreational endurance runners present a rearfoot strike nowadays (62,84,96,97). This evolutionary alteration has been attributed to current modern running shoe designs with the introduction of impact attenuation systems, such as increasing the thickness of the midsole or increasing the thickness of the heel relative to the forefoot, also known as the shoe's drop (98). A systematic review examining the risk factors and gender differences for injury in endurance runners found that use of modern running shoes for a prolonged period of more than 4 or 6 months is associated with an increased risk of injury for both women and men (99).

Footstrike pattern is a variable easily measured with a high-speed camera positioned perpendicular to the runner's direction and visual observation can be used to assess it. Therefore numerous studies have studied its effects on running performance and injury prevention (48,62,84,96,100–102). The instant at which the runner's foot hits the ground is the moment when the footstrike pattern occurs, which can take three forms: a rearfoot strike (RFS), in which the heel lands before the ball of the foot; a midfoot strike (MFS), in which the heel and ball of the foot land simultaneously; and a forefoot strike (FFS), in which the ball of the foot lands before the heel comes down, ***Figure 4***.

Figure 4. Representation in images of the three footstrike patterns. Left; rearfoot strike (RFS). Middle; midfoot strike (MFS). Right; forefoot strike (FFS).

Different footstrike patterns have been observed among runners of different disciplines depending on distance and running speed. For example, forefoot strike is more prevalent among short distance runners, or sprinters, but rearfoot strike is more prevalent among endurance runners today (62,84,96,100,101,103–106). However, in habitual barefoot runners the prevalence of forefoot support is the most dominant (85,107).

The moment the foot hits the ground the runner's musculoskeletal system experiences an increase in tension and internal loading, especially in the foot, tibia, knee, femur and hip (along the lower limbs) (108,109). The mechanics of the landing of the runner at the moment at which the collision occurs has been extensively documented in the literature (85,108–111). This impact can vary in relation to the footstrike pattern the runner presents (85,110,111). For example, the prevalence of a rearfoot strike is associated with a high and abrupt vertical impact of ground reaction force as opposed to a forefoot strike and midfoot strike where no such abrupt impact is observed, but rather a smooth and progressively ascending curve from initial contact to the active peak of vertical force. This has been observed because forefoot strike increases the eccentric loading of the posterior portion of the calf muscles, significantly reducing the vertical peak impact after initial contact (112,113).

Since the appearance of an abrupt peak appears mainly in rearfoot strike, some studies have simplified the footstrike pattern into two forms: rearfoot strike and non-rearfoot strike (encompassing both forefoot and midfoot strike) (48,114). The classification of footstrike pattern between rearfoot strike and non-rearfoot strike has shown better results related to a higher accuracy to systematic observation for the determination of rearfoot strike (interrater accordance: 0.981), compared to the determination of rearfoot strike between mid and forefoot strike (interrater accordance: 0.893), due to the increased options, the similarity between midfoot strike and rearfoot strike and forefoot strike being a difficult footstrike pattern to classify (115).

From an applied training and clinical point of view, the theoretical connection has opened the debate that the vertical load produced when the runner lands on the ground has a close relationship with the foot strike pattern, and the latter has been hypothesised as a possible cause of overuse running-related injury in recent literature (18,85,116). Specifically, the prevalence of rearfoot strike has been associated as the foot strike pattern risk factor related to impact injuries in runners because it has been associated with an abrupt, high-impact peak in ground reaction force, increased peak tibial acceleration and increased ankle stiffness after initial contact. (85,117–122). Conversely, the forefoot strike due to the absence of the initial impact peak has been suggested as a footstrike pattern that is less susceptible to high impact related injuries (18,116).

A recent case series study suggested that an intervention transitioning to forefoot strike running can reduce anterior compartment pressures in patients with anterior chronic exertional compartment syndrome, leading to a concurrent reduction in participants' symptoms (123). The authors suggested that this improvement may be due to a reduction in tibialis anterior muscle activity, which is required to eccentrically control ankle plantarflexion during running in runners with a rearfoot strike (123,124).

In addition, a long-term intervention found that after a period of transition to forefoot strike, the vertical load at impact decreased and the runners' baseline cadence increased (122). Baggaley et al. (119) compared three real-time visual feedback components during a single session, which included: targeting a FFS by using foot strike angle (FSA) as visual feedback, decreasing baseline step length by 7.5% and decreasing baseline vertical loading rate by 15%. The forefoot strike visual feedback was the strategy that reduced impact attenuation the most compared to the other visual feedback components.

The simplicity of measuring the footstrike pattern has led to numerous studies, yielding associations with other parameters that are also easy to measure and manipulate. For example, stride length can be affected by the type of footstrike pattern (47,48). The forefoot strike has shown a shorter stride length with the foot placed close to the centre of mass of the body. In addition, an increased prevalence of forefoot strike in recreational runners has been shown to increase cadence and decrease stride length (117,123,125,126).

These biomechanical changes have been associated with a reduction in the moment arm of the ground reaction force to the lower limb segments, especially for the knee and hip joints. In this regard, several acute and long duration studies have manipulated the basal cadence of runners by reducing stride length by 10% in runners with rearfoot strike (45,46). These authors observed significant decreases in knee and hip joint moments, as well as reductions in peak impact and loading ratios after a 10% decrease in stride length, being hypothesised as potential risk factor reduction variables

(18,116). In addition, increasing stride length could also be beneficial for bone health, reducing the likelihood of tibial stress fractures, even though basal cadence increases (42).

Some other biomechanical effects to consider in relation to the forefoot strike are an increase in plantar flexion and an increase in the knee flexion angle at the instant of impact, resulting in a more equitable distribution of the impact reaction force over a larger surface area, improving shock absorption, than if the entire impact is concentrated on the heel alone as with the rearfoot strike (127,128). In addition, the plantar fascia has been proposed to be useful in providing a support system along the arch of the foot, acting as a shock absorber, and facilitating elastic restitution during running that could be used during barefoot running (118,127).

The transition to a more anterior footstrike partners such as forefoot strike, will result in an alteration of eccentric forces in the joints, with an increase in eccentric work of the ankle and a concomitant decrease in the load on the knee joint (129) which could be beneficial for knee injuries (130–132). We must bear in mind that the knee is the region with the highest risk of injury among endurance runners (21).

However, we must be cautious and pay special attention to ankle or plantar fascia injuries as this could lead to an increased risk of forefoot strike. In addition, although footstrike pattern is often cited as one of the factors used for injury risk stratification in runners (133), other factors such as running environment, lower body kinematics, training load planning, fitness level, shoe type and anthropometric parameters of the runner must be considered (134).

THE FOOTSTRIKE PATTERN IN REAL COMPETITION

Despite the numerous studies that attempt to define the importance of stride pattern by understanding its beneficial and counterproductive effects on the health and performance of runners (48,62,110,111,114,127,128,84,85,96,100–102,108,109), few studies have been conducted in real competition environments with large masses of recreational runners (e.g. 5k, 10k, half marathon, marathon, etc.) (62,84,96). However, the drawback observed in these studies was that they did not perform intra-participant observation at various points during the race. Thus, they were unable to establish associations between how the footstrike pattern evolved during the race, for example, by taking different measurements during the competition, as well as other biomechanical variables of interest.

To date, studies in real-life competitive situations by Bovalino et al. (106) and Larson et al. (135) have tracked footstrike pattern and kinematic variables in large populations of recreational runners over various stages of the race. These studies noted in their findings that a large percentage of runners changed their footstrike pattern from non-rearfoot strike to rearfoot strike, from a race point located at the start to a race point located at the end (closer to the finish) of the race. However, these studies omitted comparing the effect of changes in classification with the runners' footstrike pattern and biomechanical parameters during the race. Therefore, few studies have been conducted on the analysis or monitoring of how footstrike pattern and biomechanical parameters could affect an intra-runner, and none have considered how these biomechanical parameters affect performance, e.g., by considering the runner's position during the race between stages.

1.2. BAREFOOT RUNNING: ORIGINS AND BIOMECHANICAL IMPLICATIONS

THE ORIGINS OF BAREFOOT RUNNING

As suggested by Bramble and Lieberman in their publication in Nature in 2004, humans were *"born to run"* (5). The authors draw on fossil evidence by analysing our anatomical structure, as well as making comparisons with other mammals such as horses, chimpanzees, or our ancestors such as *Homo erectus* and *Australopithecus afarensis*.

One of the factors to be taken into account when analysing the evolution of homo towards long-distance running is the impact resistance that the skeletal system must withstand. Running, unlike walking, increases the exposure of the skeletal system to greater stresses caused by impact. This is because running includes a flight phase in which no part of the body is in contact with the ground, leading to an increase in the impact of the foot against the ground, which is more pronounced than in walking, where there is no flight phase (110). Thus, anatomical features found by Bramble and Lieberman (5) in Homo sapiens compared to other hominids and chimpanzees, such as a more upright posture, a narrower pelvis, longer upper and lower limbs, and a narrower and shorter trunk, have been hypothesised to be beneficial for impact attenuation during running.

Accordingly, just in the region of the human foot alone we have a total of 26 bones, 33 joints and 19 muscles (136). The bones of the foot, from the rearfoot to the forefoot, are favourably positioned for mechanics capable of supporting body weight and distributing loads along the length of the foot during human locomotion thanks to the arrangement of the medial longitudinal arch (137). Additionally, to the skeletal structure we must add the complex system of muscles at different depth layers to control bipedal balance and human movement (138), together with the presence of 104 cutaneous mechanoreceptors located only on the bottom of the foot (139).

In addition to the characteristics of Homo sapiens for running, there were important survival-related reasons that could lead humans to run long distances. These changes occurred at a time when Homo's brains increased considerably in size, increasing the demand for fat and protein (5). Hence, prior to the invention of different hunting tools, such as spears, bows and arrows, Homo sapiens had to hunt their prey to the point of heat exhaustion in order to satisfy their fat and protein demands (6).

Other proposed survival techniques linked to long-distance running have been competition with other scavenging mammals or even other hominids to reach prey before them (5). However, there is no scientific evidence regarding the occurrence of running-related injuries in early Homo populations, even though running may have been necessary for survival, in particular barefoot running or running in technologically unsophisticated footwear (e.g., sandals) (140).

This early hominid running is supported by barefoot running theory, concluding that Homo sapiens evolved adaptations for optimal barefoot running, such as minimising impact, increasing proprioception, and increasing foot muscle strength (140). Thus, it has been hypothesised that barefoot running helps to prevent injuries (140). Furthermore, it has been proposed in several studies that long-distance running is in the genes of Homo sapiens on the basis of many distinctive features, with running being considered part of current human evolution, especially barefoot running, described as the most natural form of running (5,140).

EVOLUTION OF RUNNING FOOTWEAR OVER THE YEARS

Although humans began to walk or run barefoot, over the course of time different types of footwear have been designed. There is evidence that early humans have been wearing footwear in the form of sandals or moccasins for the last 40,000 years (141). The design and manufacture of this footwear was simply to offer protection of the plantar surface of the foot to the human being. Over time, human beings have been progressively adapted to the increasing use of footwear in their daily lives (141). Pinhasi et al. (142) described the Chalcolithic shoe, **Figure 5**, a type of footwear among Old World populations, providing strong evidence that humans wore shoes between 3627 and 3377 BC.

Figure 5. Image of Chalcolithic in the Near Eastern Highlands, by Pinhasi et al. (142).

During the 19th and 20th century, the first technological advances in sports footwear emerged. The first running shoe was not manufactured until 1890, by J.W. Foster and Sons under the brand Reebok in Canton (Massachusetts, USA) (143,144), **Figure 6.** This first running shoe was very popular for its time due to its innovative design and manufacture, as it was made of leather with several spikes in the forefoot to promote traction of the foot to the ground. Then, the first sneakers made of vulcanised rubber were manufactured in 1917, under the brand Keds Champions in Richmond (Indiana, USA) (145). In 1925 the first spiked running shoe adapted for different foot types was produced by Adolf Dassler, also known as Adi-Dasler under the brand Adidas in Herzogenaurach (Germany) (146,147), **Figure 6**.

Figure 6. Left: Running footwear manufactured by J.W. Foster and Sons under the Reebok brand in Canton (Massachusetts, USA) in 1890 (143,144). Right: First spiked running shoe produced by Adolf Dassler, also known as Adi-Dasler under the brand Adidas (146,147).

However, it was not until the 1960s and 1970s that running shoes underwent a remarkable evolution thanks to the application of technological advances in their design and manufacture. Accompanied by the huge expansion of endurance running, which became one of the most popular physical activity activities, the sales demands for running shoes increased. These advances included the introduction of lighter materials for shoes, a raised heel to move the centre of gravity forward and promote forward motion, motion control systems for better stabilisation of the foot, and mid-soles with high absorption capabilities to improve shock attenuation (6,102,148). Such new elements in sports footwear have provided footwear brands with marketing strategies to target specific goals like comfort, injury prevention, improved athletic performance or correction of movement patterns (e.g. for pronated or supinated feet) (6,140).

This transition to the modern running shoe began with Asics with the Ontisuka Tiger shoe that used cushioned heels (149,150). Originally known as Onitsuka Co., Ltd. (after the name of the founder, Kihachiro Onitsuka), in Kobe City, Japan. Ontusuka Tiger was bought in 1963 by Phil Knight (co-founder of Nike, Inc., USA), initiating a relationship with Nike, Inc (originally known as Blue Ribbon Sports) (149,150). However, this relationship did not last long, and years later it fell apart, leading to mutual lawsuits and the separation of Asics and Nike (150,151). In 1972, Phil Knight together with Bill Bowerman (coach and co-founder of Nike, USA) developed their own design separate from Asics, with the running shoe known as the Nike Cortez (151,152), **Figure 7**.

Figure 7. Left; the current Onitsuka Tiger MEXICO 66 model, inspired by the LIMBER model worn by the Japanese national team at the 1968 Olympic Games (150). Right: Nike Cortez model, by Phil Knight and Bill Bowerman from 1972 (151).

In 1974, Bowerman came up with the lightweight but expensive running shoe known as the Waffle Trainer (151,152). Bowerman always aimed to design a shoe that was as light as possible without losing ground traction and experimented with a new technology (151,152). This new technology grew out of an in-house waffle mould which, together with the use of melted urethane, a compound used to make high-performance soles and floors, led Bowerman to design the revolutionary shoes of the time. Basically, he used the iron-shaped depressions used to make waffles, but in inverted form as an excellent mould for a lightweight sole without losing traction, **Figure 8**.

Figure 8. Nike Waffle Trainers from 1974 (151,152).

Finally, from the beginnings of modern footwear in the 1970s to the present day, features such as motion control and stability have consistently appeared in the modern shoe (153). To this end, modern footwear has introduced technologies such as a dual density midsole, a raised and cushioned heel, arch support, and a rigid heel counter, among numerous other elements depending on the brand's targets, to improve foot control and impact attenuation (153). These additional features are intended to aid foot function for running performance and reduce running-related injuries. However, the benefits of these technological innovations in injury prevention have often seen inconsistent results in the present (153,154).

A recent systematic review in 2021 by Azeem et al. (155) found that modern running shoes lack efficacy in preventing injuries, despite being hypothesised to have potential benefits for running-related injuries. Highly cushioned, motion-controlling shoes have been shown to be unnatural and therefore may be central to the high injury rate of modern runners.

SIMULATING BAREFOOT RUNNING THROUGH MINIMALIST SHOES

Barefoot running has been gaining popularity for endurance runners in recent years, both because of the large scientific output measured in scientific publications and its popularity in the media, both suggesting numerous benefits for endurance runners. The popularity of barefoot running in the media started with the book "Born to Run" written by C. McDougall (156), which brought barefoot running to runners, scientists, physicians, and coaches.

From a scientific point of view, several publications related to both our body structure and fossil findings suggest that we are "born to run" due to the design of our musculoskeletal system, unlike other hominids (1,2,5), in addition to the fact that 40,000 years ago the first hominids ran barefoot or with sandals (5). Another popular area in academia is the relationship that has been generated between barefoot running, the footstrike pattern and impact attenuation that has been suggested as a benefit for impact-related injuries (85,108–111). In summary, the hypothesised benefits have been a reduced risk of impact injury, more economical running, and more natural running for the evolutionary biomechanics of Homo sapiens.

Because of the emerging popularity of barefoot running and the scientific evidence of its potential benefits in science, several shoe manufacturers have begun work on the design and manufacture of minimalist running shoes. These shoes aim to simulate barefoot running, without actually being barefoot. Thus, minimalist running shoes have the following characteristics: they are light, flexible, with minimal thickness and maintain the shape of the foot without compressing it (107,157–160).

Some of the best known brands and models of minimalist running shoes are Vibram in Albizzate (Varese, Italy), who designed the FiveFinger model, which was launched in 2006 as a kind of glove for the foot and toes like a second skin (161–163), Nike Inc. (Beaverton, Oregon, USA), who designed the Nike Free model (164), Saucony Inc. (Lexington, Massachusetts, USA), who designed the Saucony Kinvara model (153,165), and finally New Balance (Boston, Massachusetts, USA), who designed the New Balance Minimus model (153,166,167), **Figure 9**. These last three manufacturers are popular for their conventional running shoes, with origins in running and other sports. They decided to expand their market through the design of minimalist footwear versions. To do so, they try to manufacture lighter, more flexible footwear with less cushioning and motion control systems than the rest of their footwear catalogue (153).

Figure 9. From left to right: Vibram Fivefingers, CVT LB Mens Green Beige model (168), Nike Free model (169) and New Balance Minimus TR model (170).

Preliminary results for minimalist shoes are promising as they simulate barefoot running in many biomechanical parameters. A laboratory study by Lieberman D.E. et al. (85) examined running biomechanics using Vibram FiveFingers shoes in 14 habitually shod runners where 10 runners showed an RFS pattern at the start of the study. The authors observed that after 6 weeks of transition and use of the Vibram FiveFingers, the runners reduced dorsiflexion of the ankle joint at initial contact and increased ankle flexibility during impact, which decreases the effective mass of the body hitting the ground, similar to a transition to barefoot running (171).

A 6-week intervention to transition to Vibram FiveFingers in 12 female endurance runners showed some similarities from minimalist footwear to barefoot running (162). After 6 weeks, the authors observed; a decrease in tibialis anterior muscle activity in the pre-activation phase, as well as a reduction in stride length, stride duration and flight time, and an increase in cadence, similar to changes associated with barefoot running (48,114,171). In addition, the authors observed a significant increase in gastrocnemius pre-activation amplitude compared to running in modern, cushioned shoes. Overall, the six-week transition to Vibram FiveFingers was associated with a significant decrease in loading rates and impact forces, which has been hypothesised to reduce risk factors (131,132). Similarly, McCarthy C. et al. (163) conducted a 12-week transition to the Vibram FiveFinger in female runners yielding more evidence. The 12-week intervention demonstrated a transition to forefoot strike, as well as a reduction in ankle joint dorsiflexion and an increase in knee flexion, both at initial contact. Thus, helping the runners to adopt a more forefoot strike pattern and kinematics similar to barefoot running.

However, according to the scientific literature it is not clear that minimalist shoes can provide additional benefits to barefoot running. Hein T. and Grau S. (164) compared the acute effect of barefoot running for habitual runners versus running with the Nike Free 3.0 (Nike Inc., Beaverton, Oregon, USA). The authors found that the Nike Free 3.0 mimics some characteristics of barefoot running quite well. However, differences were observed, with barefoot running exhibiting a flatter foot placement, greater plantar flexion of the ankle joint and a less inverted rearfoot, especially at initial contact, compared to running while wearing the Nike Free 3.0.

Another study that showed inconsistencies between brands of minimalist shoes for similar barefoot running was conducted by Squadrone R. et al. (165). This study compared 8 different conditions: (1) barefoot, (2) cushioned stability shoe (Saucony® ProGrid™ Guide™), and five running shoes labelled as minimalist running shoes by their manufacturers, including (3) Newton Running® MV2, (4) New Balance® MR00GB, (5) Nike® Free™ 3.0V4, (6) Inov8® Bare-X™ 200, (7) Vibram® FiveFingers® Seeya™ and (8) Saucony® Kinvara™2. Their results confirmed that not all minimalist shoes simulate barefoot running in the same way. They confirmed a higher prevalence of rearfoot strike in the cushioned shoe condition and a higher prevalence of forefoot strike in the barefoot running condition, as found in numerous studies (172–176). However, not all minimalist shoes simulated this variable. For, Newton Running, Saucony Kinvara and Nike Free 3.0 shoes did not reduce the prevalence of rearfoot strike, showing similar running kinematics to the cushioned shoe condition. Only the minimalist New Balance, Inov8 Bare-X and Vibram FiveFingers shoes decreased the prevalence of rearfoot strike, simulating barefoot running.

However, these are not the only studies that have observed inconsistencies in the results found between minimalist shoes and the similarity of barefoot running. Studies by Bonacci et al. (177) and Sinclair et al. (178) concluded that the running mechanics of minimalist shoes do not appear to closely mimic the kinematics of barefoot locomotion in experienced runners.

Therefore, not all models labelled as minimalist shoes simulate barefoot running. It seems that minimalist shoes with a low heel height, a low heel to forefoot drop and minimal cushioning capacity for shock absorption are the most likely characteristics to simulate barefoot running. Runners, clinicians, and coaches should be very cautious when recommending minimalist shoes because not all shoes will respond in the same way in running kinematics, or not all minimalist shoes will simulate the benefits of barefoot running if that is their goal. So, running in a minimalist and lightweight shoe is not the same as running barefoot.

BAREFOOT RUNNING ON RUNNING KINEMATICS

Numerous studies have documented the changes of barefoot running on running kinematics. Encompassing both changes in spatiotemporal parameters and angular kinematics. Cadence has been a widely studied variable (48,172,179–182), probably due to its ease of measurement, since there are technologies for it that do not require in-depth knowledge of biomechanics for its calculation, obtaining the variable is relatively fast and the costs of the equipment/sensors are not high, in addition to the easy implementation of its use in the applied field. Cadence, also known as step (or stride) frequency, is defined as the number of steps (or strides) a runner takes in a certain period of time, for example a second or a minute (183,184). Specifically, the effect of barefoot running has been associated with an increase in cadence (48,118,127,128,173,177,185), likewise, an increase in cadence has been associated with a decrease in lower limb loading forces, such as the instantaneous and average vertical ground reaction force at footstrike (45,46,185).

For instance, Squadrone R. et al. (185) observed an average cadence of 172 steps per minute in the footwear condition for habitual runners which increased to 182.4 steps per minute for the barefoot running condition. Similarly, Bonacci J. et al. (177) observed an increase in cadence, from 181.30 ± 8.1 steps per minute in the shod condition to 187.74 ± 9.49 steps/minute in the barefoot running condition. In the study by Wit B. De et al. (118), the shod condition showed a cadence of 164.8 steps/minute and the barefoot condition 172.8 steps/minute, as the average of three different speeds carried out during this testing protocol. Therefore, the acute effect of barefoot running could increase the basal cadence presented by running with cushioning shoes by 4-6%, according to these authors.

In relation to the increased cadence of barefoot running in comparison with shod running, there has also been an associated decrease in stride length (162,177,185,186), which has also been associated with a reduction in vertical ground reaction forces at footstrike (45,46,185). Bonacci J. et al (177) observed a stride length of 3.04 metres in the cushioned shoe condition, which was significantly reduced to 2.94 metres in the barefoot running condition. With shorter stride lengths for both conditions in experienced barefoot runners, Squadrone, R. and Gallozzi, C. (185) found a reduction in stride length of up to 2.19 metres for the barefoot running condition and 2.34 metres for the cushioned shoe condition. In other words, runners who are usually barefoot have a shorter stride length in the barefoot running condition compared to the shod condition, and it is the cushioned running condition that increases their stride length.

From another perspective, a 6-week intervention to transition to barefoot running with habitual shod runners demonstrated a reduction in stride length from 1.76 metres in the shod condition to 1.59 metres after the 6-week intervention (162). In addition, this latest longitudinal study confirmed the combination of increased cadence and reduced peak vertical ground reaction force following footstrike after the barefoot running transition for habitual shod runners (162).

Numerous changes have been documented for barefoot running in relation to the angular kinematics of lower limbs. Beginning with the kinematics of the ankle joint, barefoot running has been associated with greater ankle plantar flexion at ground contact compared to running in shoes (90,116,118,127,140,177,187,188). This more plantarflexed ankle position would suggest a higher prevalence of forefoot strike for which dorsal flexion is reduced compared to a rearfoot strike, as mentioned in the previous section (127,128). During a forefoot strike the metatarsal heads will contact the ground before the heel. In this line, the studies of Divert et al. (128) and Divert et al. (127) showed an association between a forward stance and increased plantar flexion of the ankle at ground contact, leading to an improvement in shock absorption.

In terms of frontal plane, the ankle has shown changes between barefoot running and running with cushioning shoes (118,189). Specifically, previous findings have shown a decrease in the initial and maximum ankle eversion angles when running barefoot compared to cushioned shoes (118,189). This means that wearing cushioned footwear may increase pronation during running which may be associated with an increased risk of injury. Since, excessive pronation has been associated with posterior tibial tendon dysfunction (190,191), with pain in the tibia, ankle or foot region and medial tibial stress syndrome (192). Notwithstanding, it should be noted that pronation movement within a normal range may serve to attenuate ground reaction forces (193), thus preventing stress fractures of the tibia or femur (192).

In addition, evidence has been found of a reduction in time to maximum ankle joint eversion for barefoot running compared to running in cushioned shoes (189), which may be beneficial to running performance. This is explained by the fact that a reduction in the time to stop pronation after foot impact could facilitate early stabilisation of the foot during stance phase and prior to propulsion phase (193).

Although the knee and hip present numerous changes in relation to joint moments (see next section), few studies have evidenced kinematic changes in the hip. One of the reasons could be that many studies focus their efforts on the kinematics of the foot and ankle or on spatiotemporal parameters, because of their ease of measurement and practical application. However, changes in knee kinematics have been observed as an effect of barefoot running in normally shod runners. Barefoot running has shown an increase in the knee flexion angle in the sagittal plane at ground contact. This movement has been associated with a decrease in ground reaction force (194), which may reduce the risk of knee injury (130–132), which is the most common injury among endurance runners (21).

BAREFOOT RUNNING ON RUNNING KINETICS

In the field of kinetics, the study of ground reaction forces is a fundamental pillar for numerous studies to help the understanding of running biomechanics (98,116,118,162,178,187,195–198). Specifically, the vertical component of the ground reaction force, from which several variables represented in **Figure 10** can be obtained such as:

- The vertical impact peak of the ground reaction force or simply impact peak, also known as the instantaneous vertical ground reaction force, is defined as the first maximum peak after footstrike for the vertical component of the ground reaction force (85).
- The vertical rate of loading or simply rate of loading, also known as average ground reaction force, is an average force parameter calculated from the footstrike (e.g. using a threshold of 200 N for the start) to 90% of the slope of line to the impact peak (when impact peak is present) or by setting a short percentage of time (e.g. using the 6.2±3.7% of stance phase) over the duration of the entire stance phase (when impact peak is absent) (85).
- The vertical active force or simply active force, defined as the maximum vertical ground reaction force occurring approximately halfway through the stance phase (this instant of the phase is also known as midstance) (199).

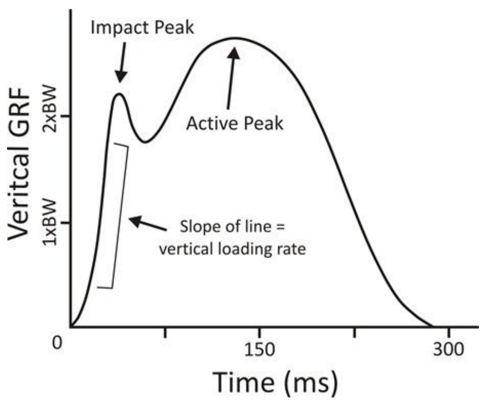


Figure 10. The vertical ground reaction force curve to represent the peak impact, rate of loading and active peak (modeled after Cavanagh and LaFortune, 1980) (199).

Of the three variables derived from the vertical component of the ground reaction force, it is the vertical peak after initial contact that has been observed to be reduced for the barefoot running situation compared to running in modern cushioned shoes (85,118,127,128,185,186,200), **Figure 10**. However, in order to improve the attenuation of ground reaction forces, some of the technological advances in modern running shoes are aimed at increasing cushioning capacity, with components such as a dual-density midsole, and a raised and cushioned heel (153). These studies have shown that barefoot running exhibits lower peak vertical reaction forces than modern cushioning shoes.

As some fossil-based studies have suggested, the human foot, by itself, is designed for barefoot running (5). These authors hypothesise that the human musculoskeletal structure has evolved to run without the use of modern footwear. One of the main variables hypothesised, in numerous studies (85,110,111), as the cause of this reduction in peak vertical ground reaction force has been the footstrike, specifically a more anteriorised footstrike, or in other words a greater presence of forefoot strikes during running (see The importance of footstrike pattern). Moreover, it has been shown to be more present during barefoot running by some recent studies (85,118,186).

However, not all biomechanical studies on running kinematics have found a reduction in the vertical peak ground reaction force. Specifically, those studies that found no difference for vertical peak ground reaction force between barefoot running and shod running conducted their experimental protocol with a floor-embedded force platform under laboratory conditions and with set speeds (118,201). Those studies that did find differences had performed the measurements on treadmills with force platforms, at set speeds (127,185). Thus, using experimental protocols on the ground or on a treadmill may contribute to some potential inconsistencies in ground reaction force results. A limited number of steps during the experimental running protocol might not encourage changes from rearfoot strike to forefoot strike (127) and non-natural and non-stable running biomechanics (202,203).

Despite this, there are studies that have recorded ground reaction forces on a platform embedded in the ground, in other words an above-ground protocol, that did find a reduction in the vertical peak of the ground reaction force. Lieberman et al. (85) did not set the running speed during their measurements, but rather the running speed was self-selected by each runner, probably allowing participants to run in a more natural way. Braunstein et al. (186) found that barefoot running at a self-selected speed on grass reduced participants' vertical peaks of ground reaction force compared to running in shoes on a track. Although, because in addition to including the barefoot running variable, there was also the variable of running on grass or track, the results could not be attributed solely to barefoot running, by the authors, but also to the footstrike pattern on which it was run.

Concerning the loading ratio, Lieberman at al. (85) observed that during the same percentage of stance phase time, the loading rate in runners running barefoot with a forefoot strike was seven times lower than in habitually shod runners maintaining their rearfoot strike when running barefoot. Similarly, Wit, et al. (118), in a study on the ground with 30 metres of running at 3 pre-set speeds, found a higher rate of loading when running barefoot with rearfoot strikes compared to running in shoes if the runners also had rearfoot strikes. Although the study observed an increase in ankle plantar flexion and flatter landing at footstrike during barefoot running, the prevalence of rearfoot strikes remained similar to running in shoes. In addition, Lieberman at al. (85) found a lower rate of loading in barefoot running with forefoot strikes than those runners habitually shod with rearfoot strikes.

Consequently, for a successful transition to barefoot running, thereby reducing both the impact peak and the rate of loading, the prevalence of rearfoot strike should be reduced. In addition, the footstrike pattern and impact attenuation has been suggested as a benefit for impact-related injuries (85,108–111,193,204). For this reason, barefoot running has been hypothesised as a method to reduce the risk of overuse running injuries from high-impact forces.

Another kinetic variable derived from the ground reaction force is the impulse, calculated by multiplying the force (or ground reaction force in this case) by the change in time (205). A study evaluating the effect of different levels of pronation on kinematics parameters during barefoot versus in shoes running found a reduction in mediolateral impulse for barefoot running (189). For the low-pronation group, they found a significant reduction in medial impulse when running barefoot versus in shoes. Conversely, for the high-pronation group, the reduction in impulse after the barefoot running condition was for the lateral peak. And total medial and lateral impulses showed no significant differences between barefoot and shod running. Additionally, Divert et al. (127), conducted a similar study comparing the mechanical impulse between barefoot and barefoot running, but did not take into account the pronation variable. They found no significant differences in peak mechanical impulse for either the vertical component or the medio-lateral component between barefoot and barefoot running.

A further kinetic variable similar to mechanical impulse is stiffness. There are two types of stiffness; i) vertical stiffness (kN·m–1), defined as the ratio of the maximal vertical force to the maximal vertical displacement of the centre of mass (92,206), and ii) leg stiffness (kN·m–1), defined as the ratio of the maximal vertical force to the maximal leg spring compression, both occurring at midstance (40,92).

According to Divert et al. (128) both vertical stiffness and leg stiffness can be between 6.5% and 7.5% higher when running barefoot compared to running in shoes. Similarly, a recent paper by Jaén-Carrillo et al (92). corroborated that barefoot running could generate a leg stiffness higher than 4% compared to shod running. This may be because modern footwear is designed to cushion and attenuate impact in order to protect the structure of the foot and leg (153,154), and this may be reducing stiffness. However, increased stiffness in runners has been proposed to improve the storage and restitution of elastic energy to the plantar flexors of the ankle (127,207), which could favour running economy for performance (208). If we also take into account that a 100g weight reduction has been proposed to improve running economy by 1% (74,209), barefoot running could be beneficial to running performance.

In addition, changes have been found in the articular moments between the barefoot and shod condition. For the sagittal plane, the main changes in force moments have been observed at the knee and hip, being lower for barefoot running than shod running (200,210,211). One of the reasons for the reduction of force moments at the knee and hip could be the design of modern footwear, which incorporates heels with a wide surface area and elevated heel height (210,212). The other reason could be the kinematic changes found from barefoot running programs, such as an increased prevalence of forefoot strikes, by reducing foot angle at footstrike, an increased knee flexion at foot strike, a decreased peak knee flexion at mid-stance (48,177,187,188), and a decreased hip flexion at footstrike compared to shod running (213). With regard to angular moments for the coronal and transverse plane, Jenkins et al. (214) found a reduction in knee abduction moment and hip external rotation moment in barefoot running.

Finally, the reductions in knee and hip joint angular moments in the different planes mentioned above have prompted the hypothesis of barefoot running as a program for the reduction of risk factors for knee injuries (130–132,213,215). Since barefoot running has been associated with impact attenuation (187,188), it has been also proposed as an non-laboratory retraining alternative for the reduction of risk injury caused by high impacts (48,216,217).

BAREFOOT RUNNING ON STATIC AND DYNAMIC BALANCE CONTROL

Barefoot running has been theorised to strengthen the intrinsic musculature of the foot and lower leg muscles, which may improve static and dynamic balance control (140). A previous study suggested a deterioration of proprioceptive abilities in the presence of tactile barriers such as the use of shoes during the aging process (218). In addition, it has been hypothesised that sensory feedback from direct foot contact with the ground enhances intrinsic muscle activation of the foot (219).

However, few studies have examined the effects of barefoot running on static and dynamic balance control. Regarding the assessment of static balance control, Squadrone at al. (220) observed better static balance control in the fully barefoot condition than in the barefoot condition with socks. Likewise, a recent study (157), which compared postural and dynamic stability and physical function between running in conventional, barefoot and 11 types of minimalist shoes, found differences. Specifically, they found that minimalist shoes improve stability and physical function in adults (middle-aged and older) compared to conventional shoes.

In contrast, an 8-week barefoot running transition programme found no improvements in strength, proprioception, dynamic balance or a change in the size of the intrinsic foot musculature (221). Thus, these authors suggested that it is possible that the benefits of barefoot running are not related to increased strength, improved dynamic balance, or improved stability, but are related to other biomechanical changes.

Therefore, due to the few studies on barefoot running and its effects on static and dynamic balance as well as the mixed findings, this information should be viewed with caution, as there is currently a lack of studies on this aspect.

BAREFOOT RUNNING ON MUSCLE ACTIVITY

The study of muscle activation patterns is another area of knowledge that can help us understand the effects of barefoot running on the human body, and thus on endurance runners. There are a considerable number of studies that have tried to shed light on this area of knowledge (92,124,127,140,160,162,187,219,222).

The phase of the run that showed the most changes in the pattern of muscle activity was the instant prior to the footstrike, the pre-activation prior to the footstrike, the instant of the footstrike and just after the footstrike. Therefore, footstrike pre-activation is the moment at which the runner approaches the end of their flight phase and the locomotor apparatus begins to prepare to land and cushion the impact (3). As for post-impact activation, it is believed that muscle activation patterns will be predefined by the characteristics of the previous repetitive impacts (223).

There appears to be an association between barefoot running and greater activation of the plantar flexor muscles (e.g. gastrocnemius-soleus) in the moments prior to the footstrike compared to run in shoes (127). One possible explanation is the kinematics of the foot with a tendency to forefoot strike and greater plantarflexion observed at impact (127,128). This could be an adaptive pattern to prepare the lower extremity for a more anteriorised footstrike. Furthermore, it may be why barefoot running has been hypothesised to be beneficial for strengthening the foot and lower leg musculature (140,219).

For instance, a 13-week training program, based on barefoot exercises, found positive structural and functional changes in plantar pressure for human locomotion, such as walking (222). This could be related to the effect of a strengthening of the intrinsic musculature of the foot, caused by an increased muscle activation of the foot and lower and rear leg after barefoot exercises. However, this study did not assess muscle activation patterns.

Similarly, a study analysed the cross-sectional anatomical areas and muscle volumes of the intrinsic foot musculature after a 12-week programme to transition to minimalist footwear, simulating barefoot running (160). The authors reported that the flexor digitorum brevis muscle increased in size by 21%, and the abductor digiti minimi muscle increased in cross-sectional area by 18% and volume by 22%. In addition, longitudinal arch stiffness increased by 60% for this study. This has been suggested to improve running economy in long distance runners by harnessing the elastic restitution of the triceps suralis (Achilles tendon together with gastrocnemius-soleus) (92,118,127).

The pre-activation of the soleus and gastrocnemius muscles may be contributing to the greater attenuation of the impact and load ratio observed during barefoot running (140,162,187). Conversely, the muscle structures of the posterior foot and ankle chain (e.g., plantar fascia, intrinsic foot musculature, Achilles tendon or gastrocnemius-soleus) may also be affected due to the excessive increase in muscle activation compared to runners with delayed stance or shock absorbing footwear (140).

Another finding related to muscle activity reported in the literature has been the lower muscle pre-activation of the tibialis anterior during barefoot running in runners who were habitually in shoes with a rearfoot strike (124). Additionally, they found that the activation sequence of tibialis anterior muscle activity after heel strike was delayed when running while wearing shoes. This has been suggested to be beneficial in reducing anterior behavioural pressure for runners suffering from anterior chronic exertional compartment syndrome (123).

Likewise, a six-week transition to simulated barefoot running induced neuromuscular adaptations in the lower foot (tibialis anterior, gastrocnemius and soleus), and their association with changes in foot strike patterns in female runners (162). The authors observed a decrease in tibialis anterior muscle activity in the pre-activation and absorption phase of running. Conversely, the study reported an increase in pre-activation muscle activity of the gastrocnemius for simulated barefoot running. This was also found to be associated with a decrease in loading rate and impact forces.

A more extensive barefoot running programme with a duration of 16 weeks of progressive loading found similar results for muscle activation (187). The muscles they tested were the tibialis anterior, gastrocnemius lateralis, long head of the biceps femoris, rectus femoris and vastus lateralis. The study reported a reduction in the overall muscle activity of all muscles when running barefoot compared to running in shoes, except for the gastrocnemius lateralis muscle which increased its activation (187).

Changes in muscle activation parameters in the studies mentioned above were associated with a reduction in loading rate, and impact forces (140,162,187). Furthermore, they have been associated with kinematic changes such as a decrease in stride length, stride duration and flight time, and an increase in cadence (162).

In summary, several studies have reported that barefoot running may increase the eccentric loading of the plantar flexor musculature of barefoot running (85), especially if there is an effective transition to a forefoot strike (85,162). This activation has been observed as an advantage for increased strength of the gastrocnemius and soleus muscles and intrinsic foot musculature (140,160,167,219), and foot stiffness (160). But it also potentially increases the risk of injury, especially leading to Achilles tendinopathies in the short term (116,117). In addition, a reduction of the lower tibialis anterior muscle, due to barefoot running (124,162,187), could benefit runners who suffer from anterior chronic exertional compartment syndrome (123). Therefore, such changes have been hypothesised to improve prevention of high impact related injuries and running economy, thereby improving the performance of endurance runners (92,118,127).

INJURIES RELATED TO BAREFOOT RUNNING

The argument in favour of barefoot running as a tool to reduce risk factors does not always fulfil this function. For example, for those individuals who habitually wear shoes and maintain their running pattern associated with shod running even when running barefoot (85). This running pattern consists of rearfoot strikes, low cadence, large stride length and contact time, and accentuated knee extension and ankle dorsiflexion at impact, among many other factors (48,118,127,128,173,177,185).

Lieberman et al (85), found that habitually shod runners who run barefoot experienced higher peak impact and loading rates than habitually barefoot runners. The authors observed that those runners who did not adapt their foot strike pattern, continuing to have a marked rearfoot strike against the ground, were exposed to seven times higher loading rates than when those same runners ran in shoes (85).

Some evidence has shown that habitual barefoot runners have suffered foot and lower leg injuries after a period of barefoot running. Stress fracture is one such injury. A case study with a sample of 10 runners reported stress fractures, mainly on the second and third metatarsal, after switching to barefoot running (224). This study by Salzler et al (224), also found one case of a stress fracture of the calcaneus. The authors suggested that a stress fracture of the calcaneus may have been the result of receiving direct loading on the heel and may be interpreted as runners who persisted with rearfoot strike running without adapting to the new barefoot running pattern instinctively. Habitual rearfoot runners have 7 times more impact force when running in shoes than when running barefoot (85).

Those runners who suffered metatarsal stress fractures after barefoot running may have experienced this as the result of adopting a forefoot landing (130,224). This has been associated with increased forefoot loading, and there are documented cases of this resulting in metatarsal stress fractures (130), most commonly in the second and third metatarsal (224). It is important to note that of these 11 reported cases, 5 runners did not undertake any progressive transition period to barefoot running, and the remainder undertook a 2–8-week transition (without detailing barefoot running volumes). Furthermore, the weekly kilometre volumes of these runners averaged 41.44 km, which could be considered average-high for an endurance runner (225). Thus, these runners do not appear to have reduced their training volume in order to switch to barefoot running.

A forefoot strike pattern during running, associated with barefoot running, has been shown to decrease the knee moment of force and, conversely, increase in the ankle moment of force, regardless of whether running with or without shoes (130). Specifically, Arendse et al. (129) found an association of eccentric loading of the knee joint extensor musculature in the moments prior to landing.

Therefore, several findings in relation to forefoot running (associated with barefoot running) have been firstly hypothesised and secondly demonstrated to have positive implications for knee injuries (130–132,213,215), having observed a reduction in the eccentric work of the knee extensor musculature, after reducing the knee extensor moment forces.

Nevertheless, it is also important to note that weak gluteal strength and limited range of motion of the posterior thigh muscles (e.g. biceps femoris, semitendonius, semimembranosus, etc) could be another risk factor for knee injuries in endurance runners (226–229). This means that the footstrike pattern is not the only risk factor associated with knee injuries, which reduces the importance of barefoot running for the prevention of knee injuries, as long as the injury factor does not come from an excess of impact forces.

If we extend the previous hypothesis that barefoot running with a forefoot strike pattern increases knee loading, but in this case consider the ankle, the opposite effect occurs. In other words, it has also been suggested that this increases the plantarflexor moments of the ankle joint and increases muscle activation of the gastrocnemius, soleus and intrinsic musculature of the foot (140,160,167,219), which could lead to an increased risk of injury to the ankle joint and foot, such as the gastrocnemius-soleus, Achilles tendon, plantar fascia or intrinsic musculature of the foot (224).

Nevertheless, while there are studies suggesting that barefoot running increases the risk of injury to the ankle joint and foot (224), other studies mention that it may prevent ankle joint and foot injuries (130,134,140,230). For example, Pohl et al. (230), suggest that barefoot running may reduce the risk of plantar fasciitis injury. This is because barefoot running reduces vertical ground reaction forces, reduces loading rate, strengthens the intrinsic musculature of the foot (140,160,167,219), and improves the elastic capabilities and stiffness of the longitudinal arch of the foot (160). However, only if the transition does not involve an excessive and abrupt change in workload for the runner will runners benefit from its effects, and this may be the case for some individuals (134,230).

For similar reasons to those stated above, repeated eccentric loads on the plantarflexor ankle muscles, such as the triceps sural, could strengthen these muscles if the load is not overstressed. In other words, controlled eccentric loads from barefoot running have been hypothesised to be beneficial in preventing Achilles tendinopathy in endurance runners (130).

Another reason why barefoot running can be dangerous is that the skin on the plantar surface of the foot may be damaged. Nevertheless, it should be noted that the plantar surface can tolerate more than 300% more abrasion loads than the hairy skin of the thigh (127). To this should be added that the damage caused by barefoot running on the plantar surface will depend on the hardness and roughness of the ground surface or the pavement on which barefoot running takes place. There have been transitional barefoot running programmes carried out on both hard and soft surfaces that reported no injuries such as cuts, bruises or abrasions (171,187,195,231–233). Therefore, bare feet will undoubtedly always be exposed to cuts, bruises or abrasions, and the level of risk will depend on interaction between the time the foot takes to adapt to barefoot running and the type of surface.

Ultimately, there is evidence for and against the risks of injury or the benefits derived from this practice. Barefoot running alone may not be of benefit to endurance runners depending on how it is conducted. An accelerated or non-existent transition to barefoot running or walking has been shown to be detrimental to endurance runners (224).

Thus, any new program for transition to barefoot running will require a period of adaptation to shed existing habits and acclimatise to the new load or new running pattern. In other words, designing a barefoot running program requires an understanding of the intrinsic and extrinsic factors of endurance runners so as not to overload the system and thus allow for adaptation of the biological structures (e.g. skeletal system or soft tissues) without increasing the risk of injury.

INFLUENCE OF BAREFOOT RUNNING ON RUNNING PERFORMANCE

The most researched variable related to running performance due to the effect of running barefoot (no shoes), or in lightweight or minimalist shoes is running economy. There is scientific evidence that barefoot running may be associated with improved running economy (73,74,209,234–239,84,85,102,106,118,135,185,196). These improvements have been widely linked to a decrease in the weight or mass of running shoes or the absence of mass as is the case with barefoot running (73,74,102,209,234). Specially, a meta-analysis on the effect of running shoe weight on running economy found that an increase in shoe weight of more than 220 g (per shoe/foot) worsens running economy (234).

However, in addition to the observed generalised effect of shoe weight on running economy, Divert et al. (74) also hypothesised possible effects of material used for the manufacture of the sole and midsole of the shoe on running economy. Similarly, several studies have suggested the possibility of manipulating the stiffness (235), comfort (236) and cushioning (237) of running shoes as other characteristics that, in addition to weight, alter running economy. However, other authors have alternatively suggested that this improvement in running economy in barefoot running is due to structural changes in the soft tissues of the plantar aspect of the foot (240). Hanson et al. (240) observed an improvement in foot elasticity in the barefoot condition compared to the shod condition, as well as a reduction in oxygen consumption.

In addition to the characteristics of the shoe (such as weight, midsole materials, stiffness, etc.) or the absence of the shoe, changes in running biomechanics or technique associated with barefoot running could affect the running economy of endurance runners. Reducing the angle of the foot strike, transitioning to forefoot strike or reducing the prevalence of rearfoot strike is one of the most commonly cited biomechanical or technical changes following the effects of barefoot running and suggested as a potential factor in improving running economy (73,85,118,185,196,239). However, it is necessary to take into account that a number of studies have observed that the footstrike pattern can be altered according to running speed (84,106,135,238) and the stiffness of the running surface (241), concluding that for an efficient transition to forefoot strike it is necessary to control running speed and even high-speed periods, and a medium contact surface stiffness.

Similarly, other spatiotemporal, kinematic and kinetic variables have been associated with improved running economy in endurance runners following a short exposure to barefoot running versus the running condition while wearing running shoes; shorter ground contact time and step length (73,74,102,118,196), greater knee flexion at initial contact (118), less ankle plantar flexion at take-off (73,118), greater leg stiffness (74,92,118,185,242) and less vertical oscillation (73,92).

Therefore, based on the several findings mentioned above, it can be hypothesised that prolonged exposure to barefoot running could be beneficial to running economy, if changes in the biomechanical running pattern or structural changes in the sole of the foot are generated. Moreover, this transition to barefoot running should be carried out on a surface with a medium level of cushioning and at a controlled speed of running.

1.3. CADENCE MANIPULATION AS A METHOD OF RUNNING RETRAINING

DEFINITION AND TYPES OF RUNNING RETRAINING PROGRAMS

The term *"running retraining"* (in Spanish known as "*reeducación de la técnica de carrera"*) has been defined as the process of learning (or relearning) a new motor pattern applied to running with the aim of generating improvements in either the performance or health of those who practice it (243).

As mentioned above, in subchapter 1.1. Overview, running for the purpose of improving the health of those who practice it (recreational runners) has led to a large mass of the population practising it (8,9). Despite this, running-related injuries in recreational runners show values of up to 74% annual incidence (16–18).

Consequently, one of the main purposes for which the scientific literature has placed the focus of acute or long-term running retraining programs has been aimed at reducing those risk factors associated with running technique in endurance runners related to running-related injuries (243).

One of the risk factors, which has been the focus of numerous and varied running retraining programs, has been the excessive load that can be placed on the knee, because of its close association with various overuse and high impact related knee injuries (131,132). Some of the variables observed are high knee strain, high vertical ground reaction force (impact, average load ratio and instantaneous load ratio) and high braking force in the opposite direction of running (131,132). One of the reasons why many running retraining programs focus on the knee is that knee injuries are the most common injury suffered by recreational endurance runners with no known acute causes (21).

Some of these running retraining programs have been performed in controlled laboratory conditions over treadmills and in single sessions using different types of biofeedback for the runner (119,122). Baggely et al. (119) conducted a single-session running retraining intervention with three different conditions. These three conditions were administered via visual feedback using a screen placed in front of the treadmill, where participants visualised either the variable; 1) foot angle at footstrike with the goal to transition to forefoot strike (foot angle less than zero), 2) a decrease in step length by 7.5%, or 3) a decrease in average vertical loading ratio by up to 15%, all with respect to the previously recorded baseline or natural running situation.

These types of running sessions were found to be effective, reducing several of the risk factors associated with running-related injuries. All three conditions were effective in significantly reducing the impact forces measured through the load ratio. In addition, transitioning to forward stance and shortening the stride length reduced the eccentric work on the knee joint. However, transitioning to forward stance increased eccentric ankle joint work. Hence, although the three biofeedback sessions for running retraining have a shared main objective, we can deduce that there are different ways of achieving it, generating technical differences between them.

Another recent study, by Huang 2019 et al (122), focused on reducing impact forces, but in this case the impact force was not used as a target variable for biofeedback of running retraining sessions, instead three kinematic variables were combined as biofeedback, and through combining them together, 12 possible combinations were created. To create the 12 combinations, the authors combined three footstrike patterns (rearfoot, midfoot and forefoot strike), two cadence modes (preferred and increased by 10% for the preferred) and two anterior trunk tilt postures (natural and with an increased flexion of 10 degrees compared to the natural). Their findings showed that the combination of heel strike with 10% anterior trunk tilt showed the highest levels of impact forces. Conversely, the forward lean, with a 10% increase in cadence over the preferred cadence reduced, impact forces the most, as well as showing the lowest levels of discomfort and perceived exertion.

However, this type of setup requires high economic costs and advanced knowledge to be able to individualise running retraining sessions using force platforms and 3D motion capture systems with real-time visual biofeedback, which are hardly available in sports clubs, fitness centres or clinics. In addition, these studies are based on a single running retraining session, so their effects are acute. And the nature of carrying out visual biofeedback limits interventions to the mandatory use of screens, limiting the space for retraining sessions to treadmills, without being able to be carried out in other environments.

In order to move out of the laboratory setting and bring running retraining programs closer to more natural environments for runners and reduce technological costs, several studies have examined the effects of both visual and audio biofeedback via mobile devices such as smart watches, pedometers or mobile phones (244,245).

The use of cadence has been a widely used variable in running retraining programs in both laboratory and field conditions, whether in interventions of a single day, or several weeks or even several months (46,47,250,251,49,50,71,72,246–249). For instant, Bramah et al. (248) examined the effects of a single retraining session in the laboratory followed by two weeks of a self-administered retraining program aimed at increasing preferred cadence by 10% by sound biofeedback using a metronome in laboratory and field conditions. However, this study consists of two weeks of running retraining by sound metronome, with a follow-up at 4 weeks and 3 months after the running session.. Moreover, the study focuses on a sample of runners with patellofemoral pain. According to the authors, their findings demonstrated that a single retraining session using a metronome to increase cadence by 10% results in significant improvements on running kinematic variables and pain in runners with patellofemoral pain. Furthermore, they observed that the changes were maintained until the 3-month follow-up after the retraining session.

Other studies have similarly used cadence increases of between 7.5% and 10% for long-term running retraining programs (several weeks) and in natural training environments outside of a laboratory (244,245).

Baumgartner et al. (244) conducted a 6-week running retraining program using a pedometer for foot motion recording and cadence calculation and a smartwatch providing visual biofeedback with the aim of increasing the preferred cadence by 10%. In addition, this system included an audible alarm that sounded when runners missed the target in five consecutive strides. This system proved to be effective, as it generated an increase in cadence of up to 8.6% after runners received biofeedback of a 10% increase in preferred cadence. The preferred cadence of the experimental group was 159.8 steps per minute and increased to 173.6 steps per minute. However, their effect on injuries, or other biomechanical or spatiotemporal parameters was not studied.

Although the Baumgartner et al. (244) system significantly reduces costs compared to those systems that have required a force platform or a three-dimensional motion capture system for their intervention, it still requires a smartwatch and a pedometer.

Finally, a recent study, conducted by Wang et al. (245) determined the effects of sound biofeedback using a mobile application with the preferred cadence increased by 7.5% for 12 weeks on biomechanical parameters. These were peak impact, vertical loading rates and lower limb running kinematics. In this case, the results showed a significant increase in runners' cadence of 5.7%. Moreover, this slight increase in cadence demonstrated a reduction in those impact risk factors that have been linked to running-related injuries, such as knee injuries. Specifically, the application of 12 weeks of audible metronome (with a 7.5% increase in cadence) resulted in a reduction in impact force, average loading rate and instantaneous loading rate, as well as a reduction in foot strike angle, knee angle and an increase in leg stiffness (245). This last variable has been associated with greater running economy by other authors (57,61,208,252).

CADENCE MANIPULATION AND SPATIOTEMPORAL PARAMETERS

Numerous studies have evaluated the effects of modifying cadence with spatiotemporal parameters. One of these variables is stride length, which has an opposite effect with cadence, i.e. if cadence is increased stride length decreases and vice versa (45,119,249,253–255).

According to Bowersock et al. (249) a 10% increase in cadence can cause a step-length reduction observed after using a metronome in a laboratory setting beeping at a 10% increase over each runner's basal cadence rate. Similarly, but through a visual feedback retraining, Busa et al. (253), observed a decrease in stride length after increasing cadence by 10% and 20%. Furthermore, Dos Santos et al. (254), after analysing the effects of 3 types of running retraining: forefoot landing, 10% increase in cadence and forward trunk lean (FTL), reported a decrease in stride length effectively after the 10% increase in cadence retraining.

Likewise, Baggaley et al. (119) compared three components of real-time visual feedback during a single session, which included: targeting a FFS using foot strike angle (FSA), decreasing step length by 7.5% and decreasing vertical loading rate by 15%. They found that decreasing stride length increased runners' cadence. They found that decreasing stride length increased runners' cadence. This is supported by Napier et al., (255) who observed that an increase in cadence decreased stride length after an 8-session laboratory-based visual biofeedback training program.

Continuing on to another widely studied spatiotemporal variable such as contact time; several authors have also found an inverse relationship between cadence and contact time (253,256). A decrease in cadence can lead to an increase in contact time. However, it is not clear that an increase in cadence can decrease contact time, according to Busa et al. (253) and Clarke et al. (256).

Moreover, a reduction in contact time has been associated with increases in running speed in long distance runners (61,257). However, it has also been observed in real running events, the runners in the fastest ranking positions and those who lost the least position during the race were those runners with the decreased contact time (62), for example during the XVII International Half Marathon of Cordoba, 2011 (Spain), which may be related to improved performance.

CADENCE MANIPULATION AND RUNNING KINEMATICS

Regarding foot, ankle and lower leg kinematics, altered cadence in recreational runners has resulted in changes mainly in foot and ankle angle at footstrike or initial contact or footstrike. Specifically, increasing cadence by 5% to 10% has been associated with a reduction in footstrike angle (45,47,254). In other words, an increase in the prevalence of forefoot (or non-rearfoot) strikes, or converting to a non-rearfoot strike pattern, has been observed.

Allen et al. (47) observed an average reduction in foot angle at footstrike of 3.34 degrees, 4.83 degrees and 7.56 degrees for the conditions of increasing cadence by 5%, 10% and 15% respectively. The baseline cadence of their runners was 165 steps per minute which increased to 173 steps per minute for the +5% cadence condition, to 181 steps per minute for the +10% condition and up to 189 steps per minute for the +15% condition, in a laboratory setting. Thus, reducing the prevalence of rearfoot strikes from 100% with 40 recreational runners at the preferred cadence to 36 runners with cadence +5%, to 33 runners with a cadence of +10% and to 28 runners with cadence +15%, this latter being the only one to show significant changes in reducing the prevalence of rearfoot strikes with respect to the preferred cadence.

Similarly, Heiderscheit et al. (45) observed a reduction in foot angle of between 2 and 4 degrees for the +5% cadence and +10% cadence conditions in a single session under laboratory conditions, while observing an association of reduced vertical excursion of the centre of mass as cadence was altered towards the increase. Conversely, these authors observed the same effect but in reverse when they reduced the cadence by 5% to 10%, with the foot angle increasing by 2 to 4 degrees, respectively, at the instant of the footstrike.

Presumably, since kinematic changes have been observed in the foot joint, we could suggest that the ankle joint would also undergo changes. As, for example, a reduction in foot angle at footstrike has been associated with a reduction in dorsal flexion of the ankle at footstrike (an increase in plantar flexion), after a period of barefoot running (90,116,118,127,140,177,187,188). However, neither Allen et al. (47), nor Heiderscheit et al. (45), nor Dos Santos et al. (254) observed significant changes in dorsal-plantar flexion of the ankle joint at footstrike. Thus, further research would be necessary to clarify.

For the knee joint, a 5% increase in cadence did not lead to changes for knee flexion or extension movements during the different phases of running (45,256). Studies that increased the basal cadence by up to 10% in runners with a heel strike have observed alterations in the knee, specifically a reduction in the peak of maximum knee flexion during the stance phase (45,250,254,258,259), and an increase in knee flexion at footstrike (45,260). Although there are also those studies that found no significant change for knee flexion in footstrike after increasing cadence by up to 10% (250,254,256).

What Heiderscheit et al. (45) observed in knee kinematics after a single-session laboratory study of increase cadence by 10% was that knee flexion tended to increase at footstrike and reduce its peak of maximum flexion during stance phase. Such changes were not found by the authors at an increase of cadence by 5% of the preferred cadence. Similarly, Clarke et al. (256) also observed no kinematic differences for the knee joint in flexion-extension when the cadence increase was 5%, but also no differences when it was 10%, for knee flexion at the footstrike.

The observed increase for knee flexion in the footstrike when the cadence is increased by 10% was 1.8 degrees on average, coinciding with both Lenhart et al. (260), 10.6% increase from preferred cadence, and Heiderscheit et al. (45), 10.1% increase from preferred cadence. As for the changes observed for the decrease in knee joint kinematics for maximum peak flexion during stance, the values range from a reduction of 2.42 degrees (6.36% lower from preferred cadence) for Bonacci et al. (259), 3.0 degrees (8.5% lower from preferred cadence) for Hafer et al. (258), 3.3 degrees (7% lower from preferred cadence) for Lenhart et al. (260) and up to 3.5 degrees (7.6% lower from preferred cadence) for Heiderscheit et al. (45). These kinematic alterations of the knee following a 10% increase in cadence in long distance runners have been associated with reduced patellofemoral joint stress, related to impact injuries (254,259).

Regarding knee kinematics, when cadence is reduced through running retraining, Clarke et al. (256) found no significant differences in knee flexion at sagittal plane. Likewise, later Heiderscheit et al. (45) reported results in the same direction, that is, no change in knee kinematics when cadence is reduced by 5% to 10% during a single session in a laboratory setting. To facilitate the understanding of their findings, it is important to note that the prevalence of rearfoot strike was very high for these studies, as only runners with rearfoot strike were studied at the beginning of their interventions. In addition, Dos Santos et al. (250) observed a reduction of the peak abduction angle (genu varum) of the knee joint from 3.22 degrees at the preferred cadence to 2.49 degrees at the 10% increased cadence.

While the main changes observed in the ankle and knee joints have been observed for the sagittal plane, and the authors have reported no changes for the coronal (or frontal) or transverse plane, several authors have observed changes in hip kinematics when we alter the cadence (increase or decrease) in sagittal and coronal planes of movement. The findings found by Heiderscheit et al. (45) and Dos Santos at el. (250) were similar for hip kinematics and both were studies where only the acute effect of a single session asking the runner to alter their cadence was observed.

Thus, after a single session in a laboratory setting increasing the preferred cadence by 10%, Heiderscheit et al. (45) observed that both the peak hip adduction angle (from 10.9 degrees to 8.7 degrees) and the peak hip flexion angle (from 26.7 degrees to 23.6 degrees) decreased during stance phase. Similarly, Dos Santos et al. (250) observed, during the stance phase, a reduction in peak hip adduction from 10.81 degrees at preferred cadence to 9.95 degrees and a reduction in peak hip flexion angle from 32.62 degrees to 30.17 degrees with cadence increased by 10%. Another recent study corroborating these findings was conducted by Yong et al. (261), who found a reduction in peak hip abduction during the stance phase of 14.4 degrees in heel-stride runners to 12.5 degrees with a 10% increase in preferred cadence. However, they found no significant changes in the sagittal plane, towards hip flexion.

Conversely, Dos Santos et al. (250) observed a significant reduction in hip flexion at footstrike of 1.54 degrees when increasing the cadence by 10% compared to the preferred cadence. However, authors such as Heiderscheit et al. (45), Yong et al. (261), Wang et al. (245) or Clarke et al. (256) did not observe changes for hip joint flexion at footstrike when altering the preferred cadence by increasing. Neither have changes been observed for the transverse plane (45,250).

The kinematics of the pelvis and trunk have been studied to a lesser extent than has been done for the foot or the ankle, knee and hip joints. Several studies have looked at increasing cadence over the pelvis and trunk (119,250,254,262) and others for reducing cadence (119,262), and in no case have changes been found for trunk flexion when cadence is altered. Except Bramah et al. (248), who after 2 weeks of out-of-laboratory running retraining based on self-administered mobile application of a 10% increased cadence, observed a reduction in pelvic tilt right at the end of 2 weeks, and a reduction in contralateral pelvic tilt permanently after the 4-week and 12-week follow-up.

CADENCE MANIPULATION AND RUNNING KINETICS

Since an association has been observed between increased cadence and reduced foot angle at footstrike (45,47,254), which could reduce the prevalence of rearfoot strike, and a reduction in the prevalence of rearfoot strike has been associated with a reduction in ground reaction force, loading rates or articular work of some joints (85,110–113), several studies have examined the relationship between altered cadence and kinetic parameters during running (44,45,264,46,122,245,249,253,254,261,263)

Many of these studies have been conducted in laboratory settings, using metronomes or visual feedback through a single session or up to 8 sessions over 2-3 weeks and kinetic parameters (44–46,122,249,253,254,261,264). Uniquely, Hafer et al (265) and Wang et al. (245) conducted running retraining in field conditions for a long period of 6 weeks and 12 weeks, respectively, with the use of a metronome for a 10% increase in cadence and observed several kinetic changes after the intervention.

Some of these findings, to date, are confusing as there are studies that have observed kinetic changes after altering the preferred cadence of runners, although other studies have observed no changes. For instance, Hobara et al. (46) observed that there were significant differences in lower limb loading rates between 5 cadence conditions.- These were the preferred cadence condition, a 15% increase and decrease from the preferred cadence, and a 30% increase and decrease from the preferred cadence. Specifically, they observed a reduction in the vertical impact of the ground reaction force, the average vertical load rate, and the vertical instantaneous load ratio when the cadence was increased by more than 17.25, 17.55 and 18.07 % respectively for each variable mentioned. Therefore, runners had to increase their preferred cadence by up to more than 15% in order for it to cause significant reductions in ground reaction forces.

Similarly, two recent studies have shown changes in ground reaction forces and joint kinetics, however, with variations of less than 15% over baseline cadence. Baggaley et al. (264), Heiderscheit et al. (45), Huang et al. (122) and Bowersock et al. (249) conducted a study in laboratory conditions using a single session per condition where cadence was increased and reduced by 10% compared to preference cadence.

The purpose of the Bowersock et al. study (249) was to examine the effects of altering cadence (using step length feedback) and the foot strike pattern on kinetic parameters such as ground reaction force and tibiofemoral joint kinetics during running in runners with a rearfoot strike. Regardless of the foot strike pattern, the authors observed that an increase in cadence resulted in a decrease in peak ground reaction force, force impulse per step, force impulse per kilometre and average loading rate at the tibiofemoral joint and medial compartment. In contrast, the condition of reducing the cadence obtained the same changes with the opposite direction, where the mentioned kinetic variables increased in magnitude. Furthermore, their findings showed that when combined with increased cadence and reduced prevalence of heel strike, the greatest reduction in medial compartment maximal strength was observed. This makes the footstrike pattern crucial for understanding kinetic changes.

Likewise, Huang et al. (122) conducted a short effect study in laboratory conditions where they combined altered foot strike pattern with 10% increase in cadence and trunk posture. Regarding the findings related to the 10% increase of the preferred cadence, the authors found a reduction of the average vertical load ratio with respect to the preferred or natural cadence. However, they found no differences for the other kinetic variables they used, such as vertical instantaneous load ratio and peak vertical impact after modifying the natural or preferred cadence. Although, as they performed other postural combinations, they observed that the most effective combination in terms of reducing vertical ground reaction forces was the one with a forefoot strike pattern and increased cadence, and conversely, the rearfoot strike with anterior trunk tilt had the highest values for instantaneous and average vertical loading rates.

The study by Baggaley et al. (264) provides related but additional information as it studies the attenuation of impacts and joint work (expressed as joint energy absorption) after altering the cadence by 10% over the preferred cadence. These authors observed that after increasing the cadence the energy absorption of the knee joint was reduced, however, a greater absorption of the ankle, which means more eccentric work during the stance phase of the plantarflexor moment for the ankle joint. Conversely, reducing the cadence resulted in more joint work for the knee (more energy absorption, or more eccentric work). Impact attenuation increased with decreasing cadence (increased step length) and decreased with increasing cadence (decreased step length), compared to the preferred cadences. It is important to note that unlike the Bowersock et al. study (249), the Baggaley et al. study (264) presented a sample with a variety of footstrike patterns, although it was predominantly the rearfoot strike, there were also runners who ran with non-rearfoot strike in the baseline condition, with preferred cadence.

Whereas Baggaley et al. (264) assessed joint work or joint mechanical energy, Heiderscheit et al. (45) studied the effects of increasing and decreasing cadence by 5% and 10% on joint mechanical energy, ground reaction forces and some kinematic parameters in acute laboratory conditions. Findings showed that after increasing the cadence by 5% and 10%, the knee reduced mechanical energy absorption, meaning less joint work, and the hip only showed significant changes by also reducing mechanical energy absorption when the cadence was increased by 10%. Thus, the knee was found to be more sensitive to increased cadence compared to the hip. The findings observed in the increased cadence condition were associated with a reduction in step length, vertical displacement of the centre of mass and maximum flexion angle of the knee joint, among its kinematic parameters. In contrast, during the 10% natural cadence reduction condition, the results demonstrated a generalised increase in mechanical energy absorption by all lower limb joints.

However, as mentioned above, there is also evidence to the contrary, as some studies have found no significant changes in kinetic parameters when cadence is altered. This is the case with the recent studies by Busa et al. (253) and Yong el at. (261). Even with cadence alterations of up to 20% (253).

Busa el at. (253), after increasing cadence by 10% to 20% from preferred cadence in a single session in a laboratory setting, observed no significant changes for peak tibial and head accelerations (assessed in the time and frequency domains) and tibial to head impact attenuation during running. Conversely, they found that decreasing cadence resulted in greater vertical accelerations of the tibia at the beginning of the stance and at the head following impact. Likewise, the findings of Yong el at (261) demonstrated no effect on average loading rate, instantaneous loading rate or peak tibial acceleration after increasing cadence by up to 20% over the preferred cadence.

Given that the studies presented so far on the alteration of cadence and kinetic parameters have been carried out in laboratory conditions and with a short effect, it is necessary to mention those current studies carried out in field conditions with a medium-long duration (245,265). Firstly, Hafer et al (265), conducted a 6-week running retraining study, in which they aimed to determine the effects of increasing cadence by 10% with respect to kinematic, kinetic and oxygen consumption parameters with a total of only 6 healthy recreational runners. The authors found that after 6 weeks of increased cadence using an audible metronome by the runners the vertical loading rate was reduced. In addition, and in agreement with previously reported kinematic results, these kinetic changes were associated with a decrease in step length and hip adduction angle, however, no changes were observed for oxygen consumption.

Secondly, a 12-week running retraining conducted by Wang et al. (245) aimed to relate how increasing baseline cadence by 10% would affect kinetic parameters, in addition to adding kinematic parameters. After 12 weeks of running retraining using an audible metronome with the cadence increased by 10% of each runner's baseline cadence, runners had significantly decreased peak impact by 10.21% of body weight, average vertical loading rate by 15.60% of body weight, and instantaneous vertical loading rate by 14.7% of body weight. Furthermore, lower extremity stiffness was found to increase significantly by 11.06% after the 12 weeks of intervention, which has so far not been proposed by the studies mentioned above. These kinetic results were associated with a reduction of the foot angle by 24.8% and the vertical displacement velocity of the centre of mass by 7.65%, both in the footstrike, as well as a decrease in maximum knee flexion by 5.44% during stance phase, after the 12-week running retraining.

In relation to the work of Wang et al. (245) who observed that increased cadence increased lower limb stiffness, Morin et al. (44) also observed that increased cadence significantly increased leg stiffness in laboratory conditions. In addition, these authors observed a reduction in contact time, vertical displacement of the centre of mass and maximum leg spring compression, which are variables used for the calculation of lower limb stiffness and could explain why stiffness may increase with increasing cadence. This could be considered an important determinant of the mass-spring mechanism of human running, which could improve running economy (84,88–91).

Another of the kinetic variables considered important for running analysis with a bearing on injury prevention (39) and running performance is braking force (63). Specifically, a reduction of the anterior-posterior braking force in both purposes. In this respect, a 10% increase in cadence has previously been associated with a decrease of the anterior-posterior braking force in laboratory settings (45,249). Heiderscheit et al. (45) found a reduction in braking force of 10.4% when the cadence was increased by only 5%, and 16.11% when the cadence was increased to 10%. Likewise, although with more conservative results, the findings of Bowersock et al (249) showed that increasing cadence by 10% could reduce braking force by 10%. Conversely, reducing the cadence by 5% could increase the braking force by up to 9.25% and reducing the cadence by up to 10% increases the braking force by up to 20% compared to the preferred cadence (45).

Finally, in terms of joint kinetics, several laboratory studies have observed no change in ankle joint work after increasing cadence by 10% (45,264). However, a reduction in negative ankle work (eccentric plantarflexion loading) has been observed when the cadence is reduced by 10% (45). For knee joint kinetics, increasing cadence by 10% has been associated with a reduction in maximal knee extensor moment (45,254,259), and a reduction in negative work (energy absorption) of the knee (75,264). In terms of hip kinetics, a reduction in hip abductor moment (45,265) and hip internal rotator moment (45) has been observed following studies in laboratory conditions by increasing the cadence by 10% over the preferred or natural cadence. Lastly, a recent systematic review and meta-analysis affirms that there are no findings related to kinetic changes in trunk and pelvis after altering the preferred or natural cadence (266).

CADENCE MANIPULATION AND MUSCLE ACTIVATIONS

In order to continue to provide information on the state of the art of altering running cadence, it is important to consider those studies that have studied its effects on muscle activation patterns (246,247,251,267,268).

In relation to findings related to muscle activation patterns in the foot-ankle region, a recent study by Swinnen et al. (246) evaluated under laboratory conditions and acute effect of 5 altered cadence conditions, such as; preferred or natural cadence, increasing and decreasing the preferred cadence by 8%, and increasing and decreasing the preferred cadence by 15%. The authors recorded the muscle activity of the medial and lateral gastrocnemius, tibialis anterior and soleus. However, only the soleus showed significant changes. Specifically, they found that the mean soleus muscle activation decreased during the stance phase of running when the cadence is increased by up to 15%. All other muscles and conditions remained significantly unchanged.

In a second study, by Swinnen et al. (251), the authors extend the information by adding the variable mean fascicle length in an article focusing on the triceps suralis. Their findings showed that the mean length of the triceps suralis is like an inverted U, showing the greatest length at the preferred cadence, so as the cadence increases or decreases the cadence to 8% or 15% this length is increased. They also recorded body energy consumption and observed that acute single-session alteration of cadence increases energy consumption, whether cadence is increased or decreased, which could affect running economy.

In a similar line of research and with the purpose of examining changes in the magnitude of the intensity of muscle activity when increasing cadence in acute situations and laboratory settings is the study by Chumanov et al (247). This research looked at increasing cadence by 5% and 10% over the preferred cadence by recording the muscle activity of 8 muscles involved in ankle, knee and hip movement: rectus femoris, vastus lateralis, medial gastrocnemius, tibialis anterior, medial and lateral hamstrings, and gluteus medius and gluteus maximus. This study focused on a sample of 45 healthy recreational runners.

Chumanov et al (247) carried out an analysis of muscle activity divided by phases of running, where they found no significant changes for the 8 muscles in the load response phase. However, in the pre-swing or early swing phase (30-50% of the running cycle), they observed an increase in rectus femoris and tibialis anterior muscle activity. In mid-late swing (70-80% of the running cycle), they observed increased hamstring activity (both medial and lateral). Moreover, during the end of the swing or pre-activation (80-100% of the running cycle), they observed an increase in gluteus maximus and medius, rectus femoris and medial gastrocnemius, whereas the tibialis anterior decreased. The authors concluded that these results, which show increased muscle activation (mainly in the gluteus) for anticipation of ground impact, as well as reductions in negative knee work (after inverse dynamics), suggest that increasing cadence may have clinical applications in runners suffering from anterior knee pain (247).

Alternatively, Connick et al (267) studied the timing of muscle activation (as opposed to intensity like the studies mentioned above) with slight alterations of both increasing and decreasing cadence of 4% and 8% using a beeping metronome. Thus, slightly more conservative alterations than the studies mentioned above. The muscles used in this study were biceps femoris, vastus lateralis and gastrocnemius. Their findings demonstrated an earlier timing of muscle activation of the biceps femoris and vastus lateralis (knee extensors), for the variables of electromyographic onset and offset, and onset and offset of the eccentric phase of the muscle. However, these authors observed no significant changes in the timing of gastrocnemius activity, either by increasing or decreasing the cadence by 4% or 8%. Nor did they observe changes after decreasing cadence for any of the rectus femoris and rectus femoris variables.

In addition, Connick et al (267) studied running economy and found that the preferred or natural cadence was the most economical compared to increasing cadence by 4% and 8%. Although, after quadratic adjustment, the authors add that increasing cadence by 2.9% would have been the most economical condition for their runners. The explanation the authors suggest for this finding is that the earlier contractions of the quadriceps muscles (biceps femoris and vastus lateralis) due to the increased preferred cadence could be associated with the reductions in knee and hip joint work observed by other similar studies (247,251), which we have also mentioned in the previous section. Therefore, Connick et al (267) suggest that although increasing cadence may generate earlier contractions prior to foot strike, running retraining by increasing the preferred cadence may have a clinical application for runners with anterior knee pain.

However, all the findings mentioned so far in this section refer to studies with short-term acute effects in laboratory settings. A recent study by Neal et al. (268) involved a 6-week intervention with a total of 18 sessions of running retraining aimed at increasing baseline cadence by 7.5% in recreational runners with patellofemoral symptom. The authors examined the effect of 18 retraining sessions, where the time running in treadmill increased as the sessions progressed in time (from 10 to 30 minutes), and conversely, the sound feedback from a metronome was progressively reduced, on the muscle activity of gluteus maximus, gluteus medius, semitendinosus and vastus medialis.

After 18 retraining sessions, their electromyography results showed only changes in the intensity of the muscle activation pattern for the vastus medialis, with an increase of activation. However, no changes were observed for the gluteus maximus, gluteus medius and semitendinosus as with Chumanov et al (247). On the contrary, improvements in the clinical symptoms of runners with patellofemoral syndrome were observed, reducing knee pain (average and maximal), as well as kinematic changes, such as a reduction in peak hip flexion and internal rotation (268).

RUNNING PERFORMANCE AND CADENCE ALTERATION

Having outlined the effects of altering cadence on running biomechanics, it is important to mention which of these effects might be related to improved running performance. As mentioned above, increasing the preferred cadence by 10% significantly reduces the load for knee (45,75,254,259,264) and hip (45,265) joints. And some of these studies have examined the effects of altering cadence on biomechanical variables related to running economy.

The braking force, a variable mentioned in the effects of altering the cadence of the kinetic group, has been associated with running performance. Specifically, a reduction in braking force can improve running mechanics and thus improve running performance (63). Studies by Heiderscheit et al. (45) and Bowersock et al. (249) showed that increasing cadence by up to 10% could reduce braking force by 16.11% and 10% compared to the preferred cadence, respectively for each study. Moreover, Heiderscheit et al. (45) observed that with slight increases of 5% of the preferred cadence the braking force can be reduced by up to 10.4% over the baseline cadence.

Another biomechanical variable associated with running performance has been contact time. Several studies have observed that runners with higher running paces have shorter contact times (61,257). The same trend has been observed during real long-distance competitions where faster runners (in front positions) had lower contact times than runners in middle or back positions (62).

Nevertheless, although increasing cadence could reduce contact time by also decreasing the prevalence of rearfoot strikes (119) and reducing stride length (255), several studies have not found a reduction in contact time with increasing cadence, in laboratory settings and single retraining session with a 10% cadence increase (253,256). Although, the authors observed an increase in contact time if the preferred cadence is reduced by 10%, which could reduce running performance (253,256).

These findings are not entirely clear because two studies, by Wang et al. (245) and Morin et al. (44), did observe reductions in contact time with increasing cadence at different cadence retraining settings. The first study was a 12-week longitudinal study with cadence increased by 7.5% using a metronome (245), and the second study was a laboratory study where the alteration in cadence was much greater, namely 30% higher than the preferred cadence (44).

In addition, these same authors who observed a reduction in contact time with increasing preferred cadence, observed an increase in lower limb stiffness (44,245), less vertical displacement of the centre of mass and less leg spring compression (44). Parameters that have been associated with an improvement in performance economy (84,88–91).

To further clarify the association between altering the preferred cadence and running performance, we must analyse those studies that include physiological variables directly related to running economy (such as oxygen consumption rate or heart rate). In this regard, studies published in the 1980s and 1990s concluded that high alterations in preferred cadence, in some cases up to 20%, could have a detrimental effect on energy cost in long-distance runners (269,270).

More recent studies by Hunter et al. (271) and Ruiter et al. (71) and Mercer et al. (272) have examined the effects of altering preferred cadence and rate of oxygen consumption or VO2. Hunter et at (271), hypothesised that an inverse relationship exists whereby reducing both cadence and leg stiffness would improve running economy (reducing oxygen consumption ratio or VO). After 1 hour of continuous running at preferred cadence and altered cadences above and below 4% and 8%, the authors observed that when runners accumulate fatigue their cadence tends to decrease and energy cost increases. Although cadence and stiffness showed a different value for each runner.

When Hunter et al (271) compared oxygen consumption between the different altered cadences, they observed that there were no significant differences between the conditions. However, they did observe that the energy cost curve in relation to different cadences presents a U-shaped curve. This means that at both high and low cadences, the oxygen consumption ratio increases, with oxygen consumption being low for the preferred cadence, but with no significant differences.

Likewise, de Ruiter et al. (71) examined the relationship between runners' self-selected natural cadence and its proximity to the minimum oxygen consumption ratio or minimum energy cost for trained and novice runners. Both experimental groups (trained and novice runners) ran at their preferred self-selected cadence and two altered cadence conditions, an 18% increase and a 18% decrease of the preferred self-selected cadence using a metronome. Using very high alternations of the cadence.

Their findings showed that although the group of trained runners was closer with their preferred cadence to the minimum energy expenditure than the group of novice runners, both groups experienced a U-shaped curve when comparing different cadence conditions and energy expenditure, as Hunter et al. (271) observed. It is notable that these differences in U-shaped energy cost between the different cadences did not show significant differences. Therefore, both studies concluded that the acute single-session alteration of the preferred cadence shows a U-shape, with no significant differences between the different cadences.

A third study by Mercer et al. (272), like Ruiter et al. (71) and Hunter et al. (271), concluded that there is no significant interaction between altering cadence and oxygen consumption ratio and heart rate. Besides, heart rate presented a U-shaped curve, as does oxygen consumption at the different altered cadences. This study used an acute alteration of cadence by 15% in both increase and decrease. This means that in acute laboratory studies where cadence has been altered by between 4% and 18% for increase or decrease, it has not been observed that increasing or decreasing cadence shows an improvement or worsening of running energy cost.

According to Connick et al. (267) a 2.9% increase in preferred cadence for their population group was found to be the optimal cadence (lowest energy cost) based on a quadratic adjustment. Furthermore, these authors supported that real increases of up to 8% of the preferred cadence in a single session would increase the energy cost, as previously mentioned by other authors (71,271,272).

A recent study by van Oeveren et al. (72), which corroborated that the heart rate curve is U-shaped when cadence is increased or decreased as Mercer et al. (272) did, also concluded that increasing cadence can reduce heart rate when running cadence at a comfortable pace is less than 166 steps per minute for novice runners. This would mean that in novice recreational runners where their preferred cadence is far from the optimal cadence (minimum energy cost), it may be useful to increase cadence by reducing heart rate, which could increase running economy. In this study the sample was novice recreational runners running at three running speeds and each speed at five different cadences, and all running speed where lower than 2,9 m/s (10,44 km/h), with 2,6 m/s (9,36 km/h) for the self-selected comfortable speed.

In a similar way, Lieberman et al. (273) concluded that 170 steps per minute was the most optimal or lowest energetic cost cadence for recreational runners running at 3 m/s (10.8 km/h), which is a low pace compared to high-level runners. Another conclusion from Lieberman et al. (273), is that for every 10 steps per minute increase in a runner, the maximum hip flexor moment increases by 5.8% and the vertical distance between the hip and the foot decreases by 5.9%, obtaining the lowest braking force values.

Therefore, it could be suggested that the optimal cadence is a relative value that should be connected to the running speed or pace and that in certain situations the preferred cadence may not be the most optimal, and that biomechanical factors such as stride type, contact time and other kinematic and kinetic parameters should be taken into account in order to draw conclusions. Finally, a recent systematic review and meta-analysis suggests that to date there is no evidence to suggest a significant detrimental effect of physiological measures (oxygen consumption rate or heart rate) on running performance when altering increasing cadence (266).

INJURY PREVENTION AND CADENCE ALTERATION

Following altered cadence, certain modifiable biomechanical parameters have been theorised or associated with reduced risk factors for injury. Thus, some of the technical changes (kinematic, kinetic, or muscular activity) mentioned above resulting from an increase in preferred cadence are associated with a reduction in injury risk factors in endurance runners.

One of the variables modified with increased cadence is the vertical ground reaction force, such as vertical peak impact, vertical instantaneous load ratio, vertical average load ratio (40–43,263) are significantly reduced. The reduction of vertical ground reaction forces produced in the running impacts after the flight phase could reduce the risk of injuries associated with high impacts (32,38,39).

Similarly, braking force, which is another variable determined from reaction force but in this case the horizontal component, has also been associated with increased cadence (45,249,263). A reduction in braking force has been linked to a benefit in reducing risk factors for footstrike impact after the flight phase of running in endurance runners (39,131,132).

Moreover, the increase in cadence has been associated with changes in joint moments and joint work of the lower limbs. Specifically with lower external sagittal moments at the knee joint and an increase for the ankle joint (40–43). These changes have been followed by several authors for reducing the load of runners' knees (45,75,254,259,264) which is the most injured joint among recreational runners (21–23).

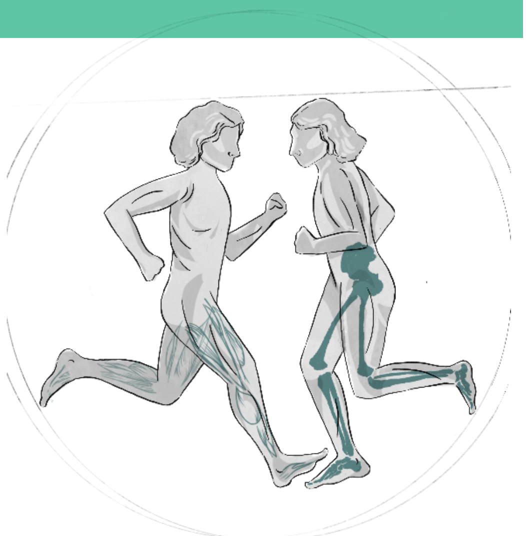
Also, certain kinematic changes have been associated with reduced ground reaction forces in the footstrike after altering the cadence towards a 10% increase in the preferred cadence. These changes are the increase in knee flexion at footstrike (45,260) and the reduction in maximal knee flexion during stance phase (45,258–260), which are hypothesised to be beneficial in reducing patellofemoral joint stress (254,259).

To date, these hypotheses have been tested by two long-term running retraining programs outside of a laboratory setting aimed at increasing cadence in recreational runners (248,268).

On the one hand, Bramah et al. (248), using a 2-week running retraining intervention aimed at increasing cadence by 10% using an audible metronome in runners with patellofemoral pain, observed a reduction in pain and an improvement in patellofemoral joint function. The authors observed that these improvements in symptomatology were maintained over a 3-month follow-up, with an observation at 4 weeks and another at 3 months.

On the other hand, Neal et al. (268) conducted a 6-week running retraining program with a total of 18 sessions and a goal of increasing cadence by 7.5% using an audible metronome in runners with patellofemoral pain. The study findings demonstrated a significant reduction in mean and maximal patellofemoral pain after 6 weeks. And in terms of biomechanical variables, the authors observed a reduction in maximum knee flexion angle and maximum hip internal rotation during the stance phase of running.

CAPÍTULO 2. JUSTIFICACIÓN Y OBJETIVOS



2.1. JUSTIFICACIÓN

Por un lado, una de las variables más estudiadas en la literatura sobre la carrera es el patrón de golpeo del pie (término en inglés: *"footstrike pattern"*) o tipo de pisada, y su importancia en los parámetros cinemáticos y cinéticos (48,62,110–114,127,128,84,85,96,100–102,108,109). El tipo de pisada ha sido asociada factores de riesgo de lesiones asociadas a la carrera y la economía de carrera en los corredores de resistencia (48,62,84,96,100–102). Sin embargo, pocos estudios se han llevado a cabo en situaciones reales de competición o sobre grandes masas poblacionales (62,84,96,106,135). Además, hasta la fecha no existen seguimientos intra-corredor en competición del tipo de pisada, la inversión y parámetros temporales, y su asociación con la fatiga o la posición de carrera durante una competición real de larga distancia.

Por otro lado, aunque existen numerosos estudios en entornos de laboratorio de una única sesión de reeducación de la carrera para examinar los efectos de aumentar la cadencia basal sobre la cinemática de carrera, y su relación con la prevención de lesiones asociadas a la carrera y el rendimiento de carrera (45,46,49,50,122,260,274–276). Pocos estudios han llevado a cabo programas de reeducación de la carrera para el aumento progresivo de la cadencia en condiciones naturales de entrenamiento (fuera del laboratorio) y a largo plazo (244,245,248,254).

Del mismo modo, numerosos estudios de laboratorio y de una sola sesión de carrera descalza han demostrado generar cambios en la biomecánica de corredor y asociaciones con la prevención de lesiones asociadas a la carrera y la mejora del rendimiento de carrera (45,46,162,173,177,178,185,187,195–198,48,218–221,98,116,118,127,128,140,157). Sin embargo, muy pocos estudios se han realizado en entornos naturales. Además, muchos de ellos han evaluado los efectos de una carrera descalza hacía una transición completa o una total inmersión. Pocos han evaluado el uso de la carrera descalza como método de entrenamiento combinado con el uso de calzado para el entrenamiento y la competición por parte de corredores de larga distancia populares (171,217) y ningún estudio hasta la fecha con corredores amateurs.

Por último, tal como se ha mencionado durante el Capítulo 1: Introducción, los hallazgos de estudios para el aumento de la cadencia basal y los estudios en carrera descalza han demostrado efectos similares sobre la cinemática de la carrera

(45,48,181,217,258). Algunos de estos cambios cinemáticos que comparten la carrera descalza y el aumento de la cadencia son: la tendencia a reducir la prevalencia de apoyo retrasado o apoyo talonador (términos en inglés: *"rearfoot strike"* o *"heel strike"*), la reducción del ángulo de flexión dorsal del tobillo en el contacto inicial, el aumento del ángulo de flexión de la rodilla en el contacto inicial y la reducción del ángulo de flexión de la rodilla durante la fase de apoyo. Sin embargo, hasta la fecha no existen estudios o evidencias científicas de los efectos de ambos programas de reeducación de la técnica de carrera (periodos carrera descalza versus aumento cadencia basal) sobre la cinemática de carrera de una misma población de estudio homogénea.

2.2. OBJETIVOS

OBJETIVO GENERAL

Analizar indicadores biomecánicos del gesto de locomoción humana corriendo, en condiciones ecológicas (en competición), y su optimización mediante el desarrollo de programas de reeducación de la técnica en corredores de resistencia amateur.

Por ello, la presente Tesis Doctoral se ha divido en dos secciones.

OBJETIVOS ESPECÍFICOS

SECCIÓN 1: *Evaluación biomecánica de la carrera en situación real de competición.*

- Determinar el patrón de pisada, la inversión y las variables espaciotemporales de una amplia muestra de corredores de resistencia durante una carrera de fondo en carretera, en función del sexo.
- Determinar el patrón de pisada, la inversión y las variables espaciotemporales de una amplia muestra de corredores de resistencia durante una carrera de fondo en carretera, en función a la posición de clasificación y la distancia recorrida.

***SECCIÓN 2**: Eficacia de dos programas de reeducación de la técnica de carrera para corredores amateurs de larga distancia.*

- Diseñar y realizar dos programas de reeducación de la técnica de carrera de 10 semanas que permitan modificar la biomecánica del corredor amateur sin necesitar materiales avanzados, de alto coste o invasivos; 1) periodos de carrera descalza; y 2) aumento de la cadencia basal un 10% mediante feedback sonoro.

- Determinar la eficacia de dos programas de reeducación de la técnica de carrera (periodos de carrera descalza versus aumentar cadencia basal un 10%) sobre el patrón de pisada, la prevalencia del apoyo retrasado y parámetros espacio temporales en corredores amateurs tras 10 semanas.

- Determinar la eficacia de dos programas de reeducación de la técnica de carrera (periodos de carrera descalza versus aumentar cadencia basal un 10%) sobre la cinemática angular de miembros inferiores (tobillo, rodilla y cadera) y tronco en corredores amateurs tras 10 semanas usando un sistema de captura tridimensional.

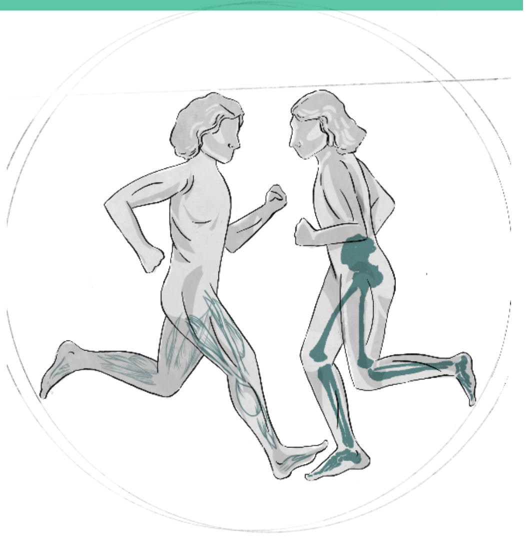
- Determinar la eficacia de dos programas de reeducación de la técnica de carrera (periodos de carrera descalza versus aumentar cadencia basal un 10%) sobre el equilibrio postural en corredores amateurs tras 10 semanas.

- Determinar la eficacia de dos programas de reeducación de la técnica de carrera (periodos de carrera descalza versus aumentar cadencia basal un 10%) sobre las presiones plantares en huela estática y dinámica de la marcha en corredores amateurs tras 10 semanas.

- Evaluar los efectos de los dos programas de reeducación técnica, llevados a cabo a ritmos confortables, sobre un alto ritmo de carrera, simulando un ritmo de competición.

CHAPTER 2.

RATIONALE AND AIMS



2.1. RATIONALE

On the one hand, one of the most studied variables in the scientific literature on running is the foot strike pattern or stride type, and its importance in kinematic and kinetic parameters (48,62,110–114,127,128,84,85,96,100–102,108,109). Foot strike pattern has been associated with risk factors for running-related injuries and running economy in endurance runners (48,62,84,96,100–102). However, few studies have been carried out in real competition situations or on large population masses (62,84,96,106,135). Furthermore, to date, there is no intra-runner monitoring in competition of foot strike pattern, inversion and temporal parameters, and their association with fatigue or running position during real long-distance competition.

On the other hand, although there are numerous studies in laboratory settings of a single session of running retraining to examine the effects of increasing basal cadence on running kinematics, and its relationship to running-related injury prevention and running performance (45,46,49,50,122,260,274–276). Few studies have conducted running re-education programs for progressive cadence increases under natural (non-laboratory) and long-term training conditions (244,245,248,254).

Similarly, numerous laboratory and single-session barefoot running studies have been shown to generate changes in runner biomechanics and associations with running-related injury prevention and improved running performance (45,46,162,173,177,178,185,187,195–198,48,218–221,98,116,118,127,128,140,157). However, very few studies have been conducted in natural environments. Furthermore, many of these have evaluated the effects of barefoot running towards a full transition or full immersion. Few have evaluated the use of barefoot running as a training method combined with the use of shoes for training and competition by recreational long-distance runners (171,217).

Finally, as mentioned during Chapter 1: Introduction, findings from studies for increased basal cadence and barefoot running studies have shown similar effects on running kinematics (45,48,181,217,258). Some of these kinematic changes that barefoot running and increased cadence share are; a tendency to reduce the prevalence of rearfoot strike or heel strike, reduced dorsal ankle flexion angle at initial contact, increased knee flexion angle at initial contact and reduced knee flexion angle during stance phase. However, to date there are no studies or scientific evidence of the effects of both running technique retraining programs (barefoot running periods versus increased basal cadence) on the running kinematics of the same homogeneous study population.

2.2. AIMS

GENERAL AIM

To analyse biomechanical indicators of human running locomotion, under natural and non-invasive conditions (in competition), and its optimisation through the implementation of running retraining programs in recreational endurance runners.

For this reason, this Doctoral Thesis will be divided into two sections.

SPECIFIC AIMS

SECTION 1: *Biomechanical running assessment in a real competition situation.*

- To establish the relationships between footstrike pattern, inversion, and spatiotemporal variables in a large sample of endurance runners during a long-distance road race, as a function of gender.

- To establish the relationships between footstrike pattern, inversion, and spatiotemporal variables in a large sample of endurance runners during a long-distance road race, according to the position in the ranking and the distance covered.

SECTION 2: Effectiveness of two running retraining programs for recreational long-distance runners.

- To design and implement two 10-week running technique retraining programs to modify the biomechanics of the amateur runner without the need for advanced, high-cost or invasive equipment; 1) periods of barefoot running; and 2) increasing basal cadence by 10% using audible feedback.

- To assess the efficacy of two running technique retraining programs on footstrike pattern, prevalence of rearfoot strike and spatiotemporal parameters in amateur runners after 10 weeks.

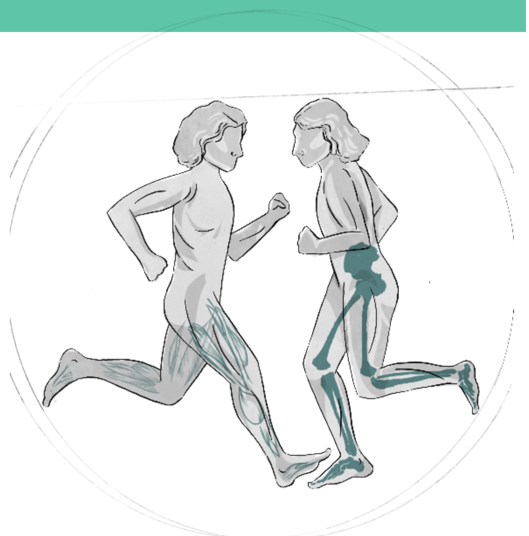
- To assess the efficacy of two running technique retraining programs on the angular kinematics of the lower limbs (ankle, knee and hip) and trunk in amateur runners after 10 weeks using a three-dimensional capture system.

- To assess the efficacy of two running technique retraining programs on postural balance in amateur runners after 10 weeks.

- To assess the efficacy of two running technique retraining programs on plantar pressures in static and dynamic gait in amateur runners after 10 weeks.

- To evaluate the effects of two running technique retraining programs, carried out at comfortable speed, on a high running speed, simulating a competition pace.

CHAPTER 3. GENERAL MATERIALS AND METHODS



3.1. GENERAL EXPERIMENTAL PROCEDURES

STUDY DESIGN

This doctoral thesis presents two study designs relates to each general aim presented in Chapter 2:

- **SECTION 1:** Biomechanical running assessment in a real competition situation. Concerning **Study 1**, Table 1.
- **SECTION 2:** Effectiveness of two running retraining programs for recreational long-distance runners. Concerning **Studies 2, 3 and 4**, Table 1.

Table 1. Summary of experimental design by study.

Study No.	Study title	Study design
1	Changes in foot strike patterns and spatiotemporal parameters in recreational runners during a half marathon.	Cross-sectional study
2	The effect of two retraining programs, barefoot running vs increasing cadence, on kinematic parameters: A randomised controlled trial.	Randomised Controlled Trial
3	Changes in running biomechanics after 10 weeks of two retraining programs: barefoot running versus increasing cadence.	
4	Effect of two 10-week retraining programs on recreational endurance runners in terms of postural balance.	

PARTICIPANTS

The study population for the present doctoral thesis was mainly recreational long-distance runners, except in the **Study 1 (SECTION 1)** where the type of runner was heterogeneous with recreational and semi-professional runners.

For the first section **(Study 1)**, no inclusion criteria were set as the runners who ran during the XVII International Half Marathon of Cordoba were analysed. A total sample of four hundred thirty-five runners (368 men and 67 women, total sample = 435) from the XVII International Half Marathon of Cordoba (Spain) were analysed.

During the **SECTION 2 (Studies 2, 3 and 4)**, the participants were recruited from three different recreational running clubs in Granada (Spain).

The inclusion criteria were as follows:

1. All the subjects were healthy.
2. All the subjects had participated regularly in aerobic training at least three times per week during the last 2 years.
3. All the subjects had no history of injury in the previous 6 months that would limit training.
4. All the subjects had run in a treadmill at least 10 times.

As regards the exclusion criteria, subjects with cardiorespiratory pathologies that affect cardiovascular performance, such as asthma, allergies, diabetes, or other cardiac pathologies, were not included.

For **SECTION 2**, a total of one hundred and ten runners (n=110) were selected, of whom 4 did not meet the inclusion criteria and 3 declined to participate prior to randomisation.

The 103 recreational runners (n=103) who chose to participate in the study and met the inclusion criteria were randomised into 3 experimental groups to carry out the different studies in **SECTION 2**. Each of the studies reflects its own flow chart, due to minor differences between studies.

CONSENT FORM AND ETHICS

This doctoral thesis conformed to the Declaration of Helsinki (2013) and was approved by the Ethics Committee at the University of Granada (No. 788/CEIH/2019). Each participant was informed about the study and signed a consent form.

Additionally, open seminars were organised for those clubs interested in participating in the study prior to the start of the data collection, with the aim of informing and answering questions from coaches and runners.

See Annexes for the original copy of the certificate of approval by the Ethics Committee of the University of Granada.

3.2. THE RUNNING RETRAINING PROGRAMS

This subsection is only relative to **SECTION 2**: “The effectiveness of running retraining programs for long-distance runners”, of this doctoral thesis. It details the intervention carried out during the Randomised Controlled Trial.

The simple randomisation method was followed, where all participants had the same probability of being assigned to the different experimental or control groups. This method satisfies the assumption of equality in the randomised groups (277).

After applying the inclusion and exclusion criteria, the sample was randomly divided into two experimental groups and a control group:

- Barefoot Group (BAR): This experimental group performed periods of barefoot retraining. The participants run barefoot on a soft, flat, grass or non-slip surface (i.e., a football pitch). Following a previously published methodology (231), this group performed the running retraining at comfortable speed, medium speed and with progressive runs building to high speed. Previous studies have shown that increasing running speed is effective in reducing the prevalence of RFS (62,231)**, Table 2.**
- Cadence Group (CAD): This experimental group performed a retraining program based on an increase of 10% of their natural cadence at comfortable speed determined at baseline following the protocol suggested by previous studies (45,46,260), and a digital metronome was used to provide auditory feedback (121). The CAD group was asked to strike their feet to the beat of the metronome and, to control the comfortable speed, the retraining sessions were performed either on a treadmill or on a 400-meter running track (controlling the pace by GPS or lap time) both within the same sporting facilities. The choice depended on the runners' abilities, those who had problems following the comfortable speed and the increase in cadence using the metronome carried out the intervention on the treadmill, Table 3.
- Control Group (CON): this control group did not perform any retraining, and the runners continued with their usual training load.

All groups continued with their training loads and habits outside of the retraining sessions, the BAR group wore their running shoes, and the CAD group did not use a metronome, during competitions, high intensity runs on the track or long distance runs in the outdoors.

The frequency of weekly sessions for the two groups that carried out the running retraining was always 3 sessions per week.

Both groups (BAR and CAD) started with 10 minutes of retraining and increased by 5 minutes every two weeks. Except for the last two weeks when they did 35 minutes and 40 minutes respectively. The first 4 weeks the retraining sessions were performance during the warm-up and the last 6 weeks were individual retraining sessions. In this way, both retraining groups performed progressive, and similar volume and intensity programs.

Table 2. Barefoot running group's weekly retraining program

Weeks	**Weekly training load**	**Total weekly time (minutes)**
1	15’ barefoot comfort pace x 3 times per week	**45**
2	15’ barefoot comfort pace x 3 times per week	**45**
3	20’ barefoot comfort pace x 3 times per week	**60**
4	20’ barefoot comfort pace + 5 progressives de 80 meters x 3 times per week	**60**
5	25’ barefoot comfort pace x 3 times per week	**75**
6	25’ barefoot comfort pace + 5 progressives de 80 meters x 3 times per week	**75**
7	30’ barefoot comfort pace + x 3 times per week	**90**
8	10’ barefoot comfort pace + 10’ barefoot medium pace + 10’ barefoot comfort pace x 3 times per week	**90**
9	35’ barefoot comfort pace + 5 progressives de 80 meters x 3 times per week	**105**
10	10’ barefoot comfort pace + 10’ barefoot medium pace + 10’ barefoot comfort pace + 5’ de barefoot medium pace + 5’ barefoot comfort pace x 3 times per week	**120**

Table 3. Cadence group's weekly retraining program

Weeks	**Weekly training load**	**Total weekly time (minutes)**
1	15' comfort pace (metronome) x 3 times per week	**45**
2	15' comfort pace (metronome) x 3 times per week	**45**
3	20' comfort pace (metronome) x 3 times per week	**60**
4	20' comfort pace (metronome) x 3 times per week	**60**
5	25' comfort pace (metronome) x 3 times per week	**75**
6	25' comfort pace (metronome) x 3 times per week	**75**
7	30' comfort pace (metronome) x 3 times per week	**90**
8	30' comfort pace (metronome) x 3 times per week	**90**
9	35' comfort pace (metronome) x 3 times per week	**105**
10	40' comfort pace (metronome) x 3 times per week	**120**

In addition, they received a weekly training diary, to check that there was at least an 85% adherence and daily retraining intensity using a 0-10 Borg scale score (278).

Apart from the instructions described above, none of the retraining groups received any other technical instruction and participants were advised to decrease the intensity of training or even abandon it when pain or injury occurred.

3.3. MATERIALS AND MEASUREMENT PARAMETERS

INFRASTRUCTURE AND FUNDING

Two scenarios were used for the data collections, the first one, related to **SECTION 1 (Study 1)**, was the XVII International Half Marathon of Cordoba (Spain). Therefore, the streets of Cordoba (Spain), where the runners in the study ran, were considered as the laboratory, as the scenario was during a real competition. Two stages of the race itinerary in an uncrowded, open environment, with a flat (horizontal) surface, and located at the beginning and end of the course were chosen (kilometre 5 and 15, respectively).

The second is related to **SECTION 2 (Studies 2, 3 and 4)**, the HuMAn Lab (Human Motion Analysis Lab), **Figure 11**, was carried out in the Instituto Mixto Universitario "DEPORTE y SALUD" (iMUDS), **Figure 12**, located in the Parque Tecnológico de Ciencias de la Salud in the city of Granada. This laboratory had the necessary technologies and spaces required for the development of this doctoral thesis.

Figure 11. Corporate image and picture of the HumanLab, where the data collection took place for Studies 2, 3 and 4 (section 2).

In addition to data collection with the HumanLab, the IMUDS was used to give pre-training talks to the runners of the different clubs to explain the project, their involvement, key dates, measurements, benefits and adverse factors. It consists of educational classrooms.

Figure 12. Corporate image (top) and pictures (bottom) of the "Instituto Mixto Universitario Deporte y Salud".

This doctoral thesis was part of the research activities carried out in two projects funded through the Spanish Government's National Plan.

- *"SISTEMA ERGONÓMICO INTEGRAL PARA LA EVALUACIÓN DE LA LOCOMOCIÓN COMO PREDICTOR DE LA CALIDAD DE VIDA RELACIONADA CON LA SALUD EN MAYORES"*; acronym: “ERGOLOC”; ref. dep2012-40069 (from October 2014 to May 2016).
- *“MONITORIZACIÓN Y FOMENTO DE HÁBITOS SALUDABLES, MEDIANTE UNA PLATAFORMA BASADA EN SENSORS PORTABLES Y ASESORES VIRTUALES, PARA LA PROMOCIÓN DEL ENVEJECIMIENTO ACTIVO EN POBLACIÓN ACTIVA Y MAYOR”* (acronym: “AVISaMe”). ref. dep2015-70980-r (from September 2016 to September 2019).

These two projects led to the creation of the present Doctoral Thesis which used the acronym **“*eRUNNING*”**.

In addition, three athletics tracks were used to carry out the running retraining programs, as they were the three training bases of the three recreational running clubs selected for the study, **Figure 13**:

1. Estadio de la Juventud, Granada (Spain).
2. Complejo Deportivo Núñez Blanca, Granada (Spain).
3. Ciudad Deportiva de Maracena, Maracena, Granada (Spain).

Figure 13. Pictures of the 3 athletics tracks used. Left: "Estadio de la Juventud" (279). *Centre; "Complejo Deportivo Núñez Blanca"* (280). *Right: "Ciudad Deportiva de Maracena"* (281).

MATERIALS

Table 4. Summary of all the materials used to carry out this Doctoral Thesis (part 1 of 2)

Instrument	**Manufacturer**	**Study No.**	**Relevant information**
High-speed camera Casio Exilim EXF1	Shibuyaku, Tokyo 151–8543, Japan	Study 1	At a sampling rate of 240 frames per second
2D video editor VideoSpeed vs1.38	VideoSpeed, Granada, Spain	Study 1	Software used to determinate the 2D kinematics data.
Professional treadmill	Woodway Pro XL, USA	Study 2 Study 3	Maximum speed 25 km/h
Floor-based photocell system	Optogait; Microgate, Bolzano, Italy	Study 2	At a sampling frequency of 1000 Hz.
3D Motion Capture System	Simi Reality Motion Systems GmbH, Germany	Study 2 Study 3	It is composed of eight high-resolution cameras operating at 100 Hz. Small systematic biases and random errors, and very high ICCs and Pearson coefficients (> 0.9) (202)
Simi Motion v.9.2.2. Software	Simi Reality Motion Systems GmbH, Germany	Study 2 Study 3	Software used for semi-automatic tracking of reflective epidermal markers.
Visual3D v.6 Software	C-Motion, Rockville, MD	Study 2 Study 3	Software used for 3D modelling, event determination and calculation of kinematic variables.

Table 4 continued. Summary of all the materials used to carry out this Doctoral Thesis (part 2 of 2).

Instrument	**Manufacturer**	**Study No.**	**Relevant information**
Plantar pressure platform FreeMed® Professional	Sensormedica, Rome, Italy	Study 4	Resolution of 2 sensors/cm2 Sampling frequency of 200 Hz. Surface: 162 x 55.5 cm; active surface: 160 x 40 cm; thickness: 8 mm
FreeStep© Standard 5.0 software	Sensormedica, Rome, Italy	Study 4	Software used for the recording and analysis of plantar pressure parameters.
Impedanciometer Inbody 230	Inbody, Seoul, Korea	Study 2 Study 3 Study 4	Dual frequency (20 kHz and 100 kHz). 8-point tactile electrode system.
Height and weight scale	SECA Instruments, Germany	Study 2 Study 3 Study 4	Accuracy to within 0.1cm and 0.1 kg respectively.

VARIABLES OF STUDY

Table 5. Summary of variables, definition, variable type, and study in which it has been used (part 1 of 4).

Variable or cluster of variables.	Variable definition and unit of measurement.	Type of variable	Study No.
Footstrike Pattern (FSP) with a five-point scale	At first contact with the ground, from rearfoot to forefoot, **Figure 14** (115): **RFS**, where initial contact is made somewhere in the heel or back third of the foot. **MFS**, where the heel and sole make contact almost simultaneously. **FFS**, where initial contact is made with the metatarsal heads.	Ordinal qualitative	Study 1
Inversion (INV)	During the stance phase, it was observed in relation to rotation on the antero-posterior axis and was registered when the shoe contacts the ground in its lateral part **(Figure 14)**	Dichotomous qualitative	Study 1
Spatiotemporal parameters	**Contact time (CT):** time for which the foot is in contact with the ground (s). **Flight time (FT)**: Time during which there is no contact with the ground (s).	Continuous quantitative	Study 1 Study 2
	Landing time: from the footstrike until the whole foot is in contact with the ground (s). **Midstance time**: from when the whole foot is in contact until the heel is off the ground (s). **Step length (SL)** (70): The distance between the point of initial contact of one foot and the point of initial contact of the opposite foot (cm). **Cadence** (70): The number of steps in a minute (steps/min).	Continuous quantitative	Study 2

Table 5 continued. Summary of variables, definition, variable type, and study in which it has been used (part 2 of 4).

Variable or cluster of variables.	**Variable definition and unit of measurement.**	**Type of variable**	**Study No.**
Three-dimensional Foot Strike Angle (FSA)	It was computed as the sagittal plane angle of the foot segment, with reference to the lab co-ordinate system at initial contact (282). Angles greater than 8.0° were represented as RFS, angles from 8.0° to -1.6° were midfoot strikes and angles less than -1.6° as FFS (282).	Continuous quantitative	Study 2
Footstrike Pattern (FSP) dichotomous	At first contact with the ground, the FSP was defined by a dichotomous classification of RFS or non-RFS. This technique has been shown to have a greater accuracy in determining a RFS (interrater accordance: 0.981), than in deciding between RFS, midfoot strike and FFS (0.893) (115).	Dichotomous qualitative	Study 2
Three-dimensional joint and segmental angles	**Three joints**: ankle, knee, and hip angle (degrees) in sagittal plane during the running cycle. **Two segments**: pelvis and thorax angles degrees) in sagittal plane during the running cycle.	Continuous quantitative	Study 3
Three-dimensional joint angular velocities	**Three joints**: ankle, knee and hip angular velocities (degrees/s) in sagittal plane during the running cycle.	Continuous quantitative	Study 3

Table 5 continued. Summary of variables, definition, variable type, and study in which it has been used (part 3 of 4).

Variable or cluster of variables.	**Variable definition and unit of measurement.**	**Type of variable**	**Study No.**
Walking plantar pressure parameters	Fick angle (degrees) Surface (mm²) and load (normalized by total load) by nine plantar zones: 1) Hallux 2) 2nd-5th toe 3) 1st metatarsal head 4) 2nd-3rd metatarsal head 5) 4th-5th metatarsal head 6) Medial arch 7) Lateral arch 8) Medial rearfoot 9) Lateral rearfoot Contact time (ms) Duration of rocker walking phases (normalized by contact time): 1) Heel rocker 2) Ankle rocker 3) Forefoot rocker 4) Big toe rocker	Continuous quantitative	Study 4
Body balance parameters from the centre of pressure (COP)	COP area (mm2) COP length (mm) COP velocity (mm/s)	Continuous quantitative	Study 4

Table 5 continued. Summary of variables, definition, variable type, and study in which it has been used (part 4 of 4).

Variable or cluster of variables.	**Variable definition and unit of measurement.**	**Type of variable**	**Study No.**
Demographic characteristics	Age (year old), body height (cm), body mass (kg), body mass index (kg/m²), fat mass (%), muscle mass (%)	Continuous quantitative	Study 2 Study 3 Study 4
Training characteristics	Comfortable speed (km/h), High speed (km/h), Training experience (years).	Continuous quantitative	
	Running sessions per week (days), Training volume per week (km). Competitions per year.	Discrete quantitative	

Figure 14. Example of footstrike pattern and inversion of the foot. From left to right: Rearfoot strike, midfoot strike, forefoot strike, and inversion.

3.4. TESTING PROCEDURES

FIELD PROTOCOL DURING A HALF MARATHON COMPETITION

This subsection is focused on the description of the field test protocol for **Study 1 (SECTION 1**) during the XVII International Half Marathon of Cordoba (Spain).

Two high-speed cameras (Casio Exilim EXF1, Shibuyaku, Tokyo 151–8543, Japan) were placed at km 5 and km 15 of the XVII International Half Marathon of Cordoba (Spain). In order to capture the sagittal plane, the cameras were positioned in a lateral view and at a distance of 5 meters perpendicular to the participants' direction of running, **Figure 15**.

Through this protocol, the variables of footstrike pattern (FSP) with a five-point scale, inversion, contact time (ms) and flight time (ms) were obtained.

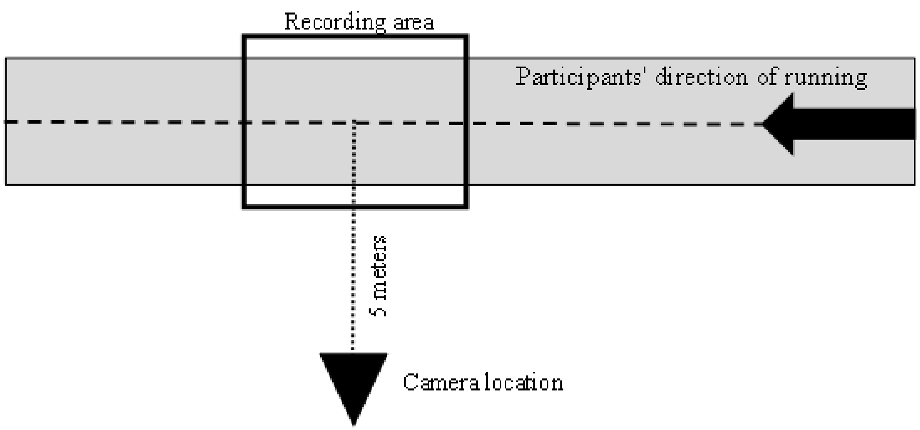


Figure 15. Overhead view of the camera position (triangle) with respect to the running direction of the runners (arrow).

DESCRIPTIVE PARTICIPANT PROTOCOL

This subsection is focused on the data collection protocol for the descriptive data for the **Studies 2, 3 and 4 (SECTION 2)**, carried out in the facilities of the HumanLab (Instituto Mixto Universitario Deporte y Salud, University of Granada).

Prior to the appointment for the treadmill running test data collection (pre-test and post-test), participants did not perform any heavy physical exertion during the previous 72 hours.

Once the participants arrived at the laboratory for first time, the first data collection carried out was to measure weight and height (SECA Instruments, Germany), To obtain the variables of "Demographic characteristics". In addition, an impedance test for body composition using a Impedanciometer Inbody 230 (Inbody, Seoul, Korea) was carried out before starting the running protocol, **Figure 16**.

It is important to note that before this first data collection, which verified that the student was well informed about the project, doubts were resolved, and the signature of the informed consent form was confirmed. In addition, this time was also used to carry out the questionnaire for the Training Characteristics variable (i.e., running sessions per week, training volume per week, competitions per year…)

Figure 16. Left: Height and weight scale (SECA Instruments, Germany). Right: Impedanciometer Inbody 230 (Inbody, Seoul, Korea).

PLANTAR PRESSURE (STATIC AND DYNAMIC) AND POSTURAL BALANCE PROTOCOL

This subsection is focused on the data collection related to the plantar pressure and postural balance protocol for the **Study 4 (SECTION 2)**, carried out in the facilities of the HuMAn Lab (Instituto Mixto Universitario Deporte y Salud, University of Granada).

The following steps are part of this protocol:

1. Walking warm-up.
2. Dynamic plantar pressure protocol.
3. Static plantar pressure protocol
4. Postural balance protocol.

Prior to the recording of the plantar pressure tests, the participants performed a 6-minute walking warm-up on the plantar pressure platform FreeMed® Professional (Sensormedica, Rome, Italy), **Figure 18**. During the walking test the instructions to the participants were: “walk at a comfortable speed, at a constant pace, without stopping”

For the walking warm-up and dynamic plantar pressure protocol, a corridor was set up inside the HumanLab with a length of 10 metres, **Figure 17**. the participants walked to the end and back, and so on for the duration of the test. After walking warm-up, a minimum of 20 footprints (10 left and 10 right footprints) per participant were recorded for the calculation of the plantar pressure parameters.

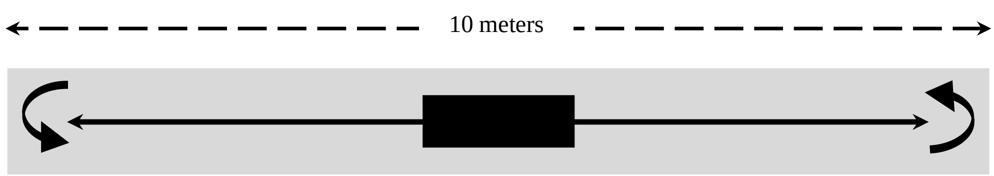


Figure 17. Graphical representation of the 10-metre corridor with the plantar pressure platform located in the centre of the corridor for the walking tests.

Once the walking warm-up and recording of dynamic plantar pressure data is completed, participants were asked to stand on the plantar pressure platform. Then, participants were asked to step onto the platform and move their arms and shoulders in such a way that they could be helped to find their natural position on the platform. Finally, the recording of the static footprint consists of maintaining an upright position on the platform for 5 seconds, **Figure 18**.

Figure 18. Left: Representation of the dynamic plantar pressure protocol. Right: Representation of the static plantar pressure protocol.

Finally, for the balance protocol, participants were asked to stand on the plantar pressure platform at 3 different tests, and all of them were repeated with open and closed eyes:

- Test 1: Bipodal, natural standing posture with self-selected foot position, for 30 seconds. Both with eyes open and eyes closed,
- Test 2: Monopodal, standing posture with dominant leg, for 10 seconds. Both with eyes open and eyes closed.
- Test 3: Monopodal, standing posture with non-dominant leg, for 10 seconds. Both with eyes open and eyes closed.

See next page **Figure 19** for the execution of the different postures of the balance protocol.

For the monopodal balance tests, performed with only one leg, the order was randomised in a simple randomisation method between right leg and left leg. Testing with eyes open first, followed by testing with eyes closed. And the position of the hands was free in all tests.

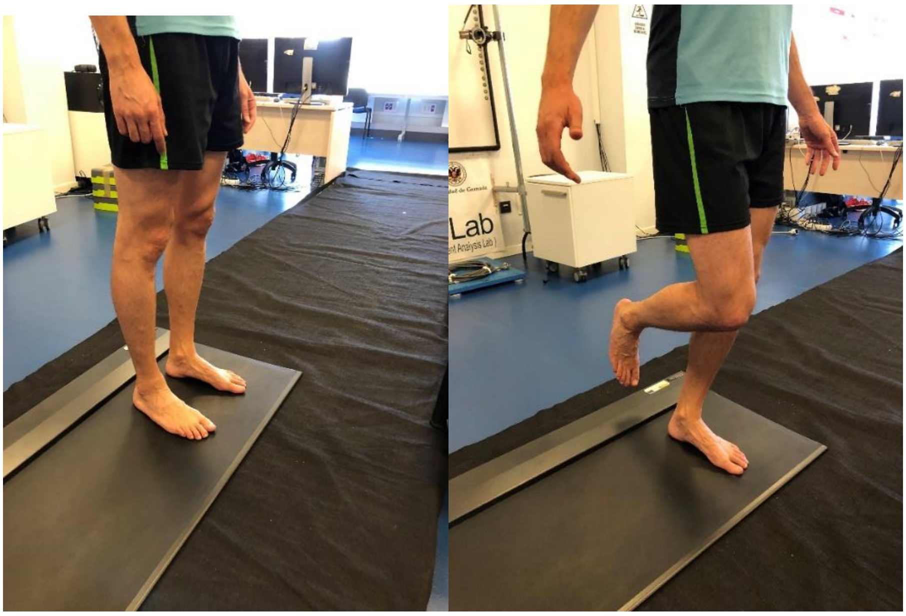


Figure 19. Left: A bipodal balance test. Right: A monopodal balance test.

PLACEMENT OF ANATOMICAL REFLECTIVE MARKERS

Before the next protocol (treadmill running protocol), Reflective anatomical markers were placed on the skin of each participant following specific anatomical landmarks for subsequent tracking and segmentation by the 3D capture system.

A total of 28 reflective markers were placed on the lower limbs, trunk, and arms of the participants according to the International Society of Biomechanics (ISB) standard (283,284), **Figure 20**.

Retroreflective markers were placed bilaterally on the acromioclavicular joint, posterior superior iliac spine, anterior superior iliac spine, femur greater trochanter, thigh, femur lateral epicondyle, femur medial epicondyle, shank, fibula apex of lateral malleolus, tibia apex of medial malleolus, second and third metatarsal heads and posterior surface of the calcaneus. Two additional markers were placed on the spinous process of the 7th cervical and 8th thoracic vertebra.

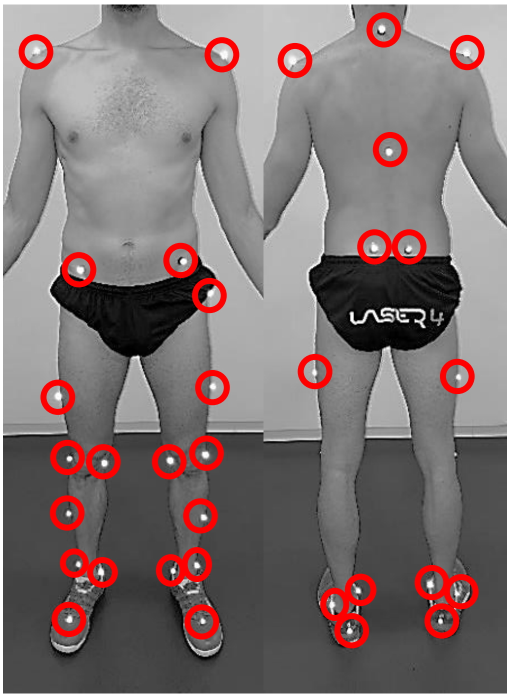


Figure 20. Image of the markers (circled) placed on a participant.

Except for the reflective markers on the running shoes, all other markers were placed on skin. For correct adherence to the skin, an adhesive in the form of a spray was used specifically for the skin. In addition, it was necessary to prepare the participants' shoes, hiding those parts with reflective material. Additionally, the reflective arm markers were not used for this Doctoral Thesis, they were required by the 3D capture system software for the auto-tracking algorithm.

Finally, two sizes of reflective markers were used, **Figure 21**:

1) Six-millimetre diameter for the lower and inner regions (e.g., foot, shank, knee and thigh), to reduce weight by avoiding dropping markers and to reduce impacts between the medial knee and ankle markers.

2) Twelve-millimetre diameter for the upper region (e.g., hip, pelvis and trunk), facilitating the auto-tracking algorithm by the three-dimensional capture software, Simi Motion v.9.2.2. (Simi Reality Motion Systems GmbH, Germany).

Both sizes of reflective markers are composed of a flexible base that facilitates adaptation to the anatomical surface of the participant in its placement.

Figure 21. Image of the passive reflective markers used, 6mm diameter marker (left) and 12mm diameter marker (right).

TREADMILL RUNNING PROTOCOL AT THE LABORATORY

This subsection is focused on the data collection related to the treadmill running protocol for the **Studies 2 and 3 (SECTION 2)**, carried out in the facilities of the HumanLab (Instituto Mixto Universitario Deporte y Salud, University of Granada).

Before starting the warm-up and running protocol, it is important to mention that a static standing recording of the participant was performed. This recording has a duration of 1 second. Participants were placed on the treadmill in an upright, standing position, facing forward with their arms separated from their hips (to avoid obscuring reflective markers). The static recording was useful to define the anatomical coordinate systems of the foot, shank, thigh, pelvis and trunk (283,284). This procedure will be explained in the following section.

Moreover, prior to the running warm-up, participants were asked to consider what their comfortable speed would be, defined as their self-selected speed at which they would train at a comfortable pace, adding the following instruction: “Run comfortably at a speed that allows you to speak and breathe easily”. In addition, they were asked to consider their self-selected high speed, defined by a self-declared recent best 5 km pace in the current season.

Once they had decided on their comfortable speed and high speed, both self-selected, the warm-up began. The warm-up consisted of running continuously for 8 minutes, starting at the participant's preferred speed, and progressively increasing the pace until reaching the comfortable speed in the last minute (70,119).

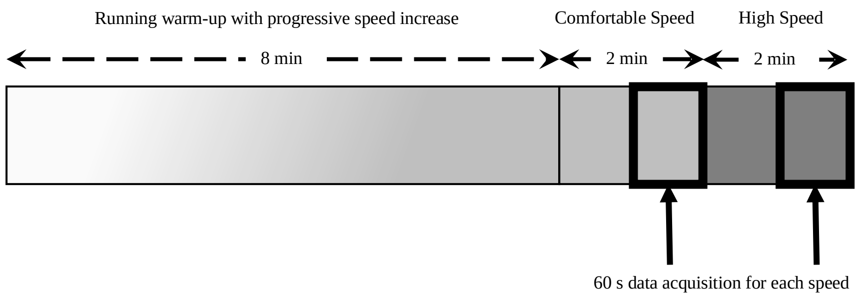


Figure 22. Graphical representation of the treadmill running protocol.

After the warm-up, the participants kept the comfortable speed, and the running data collection was carried out with a total period of 120 s. Then, the speed was then increased to the self-selected high speed to repeat with a 120 second record, after 60 seconds of stabilisation at this pace. Therefore, the full duration of the treadmill running protocol was 12 minutes, **Figure 22**.

For both speeds, participants performed the running protocol wearing their own training shoes, in a shod condition (285). In addition, to control for the possible effect of fatigue, intensity was measured using the Borg scale from 0 to 10 (278). These considerations were respected and repeated in both the pre-test and post-test. As well as the two speeds were recorded for each participant to be repeated after the 10 weeks of the running retraining program.

During the treadmill running protocol in the HumanLab, the following materials were used, **Figure 23**;

- Professional treadmill: Centred on the laboratory space.
- Floor-based photocell system: Placed on the professional treadmill.
- 3D Motion Capture System: With a ring of 8 high-speed cameras in visible range located around the laboratory walls and oriented towards the treadmill, **Figure 24**.
- Simi Motion v.9.2.2. Software: For the operation of the three-dimensional capture and video recording system.

The following variables were obtained from the treadmill running protocol, both for comfortable speed and high speed:

- Spatiotemporal parameters: Contact time, flight time, landing time, midstance time, length step, and cadence **(Study 2)**.
- Three-dimensional Foot Strike Angle **(Study 2).**
- Footstrike Pattern (FSP) dichotomous: rearfoot strike or non-rearfoot strike **(Study 2).**
- Three-dimensional joint and segmental angles: ankle, knee, hip, pelvis, and trunk **(Study 3).**
- Three-dimensional joint angular velocities: ankle, knee and hip **(Study 3).**

Figure 23. Image of the HumanLab with the treadmill centred, the photocell system placed on the treadmill, and the ring of 8 cameras placed on the bars around the lab with the LED light on.

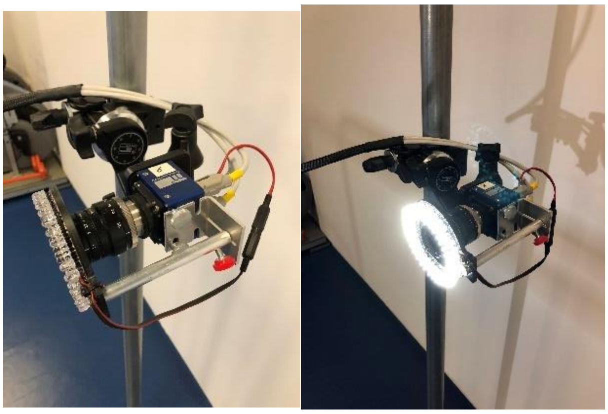


Figure 24. High-resolution camera used, model mvBlueCOUGAR-XD104C (MATRIX VISION GmbH Germany) operating at 100 Hz with a resolution of 2048 x 1088 pixels. Left: LED light off. Right: LED light on.

3.5. THREE-DIMENSIONAL DATA ANALYSIS PROCEDURES

This section details the steps followed with the use of the Simi Motion motion capture system for this Doctoral Thesis, such as 3D volume calibration, gesture capture of the run, semi-automatic tracking of the markers, filtering of the trajectories, and post-processing of the 3D tracking data.

MOTION CAPTURE SYSTEM PREPARATION

The motion capture system consisted of a total of 8 high speed cameras model mvBluecougar-XD104 (Matrix Vision GmbH, Germany) at a sampling rate of 100 Hz (100 frames per second) with a resolution of 2048 x 1088 pixels. These cameras are provided with two Gigabit Ethernet interfaces that increase the net bandwidth to 240 MB/s.

The 8 cameras of the motion capture system were placed on a bar system around the laboratory and oriented towards the treadmill, **Figure 25**. The cameras placed in front, behind, to the right and to the left of the treadmill are at approximately 4.5 metres. And the cameras placed in the four corners were approximately 6 metres apart.

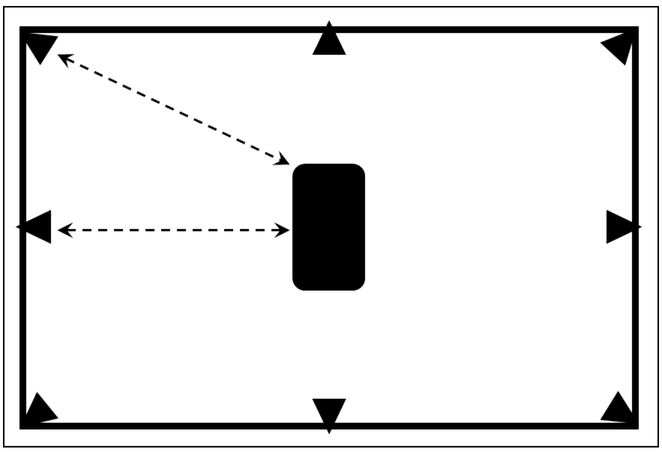


Figure 25. Graphic representation of the laboratory, with the rectangular ring of bars where the cameras are fixed (triangle), and oriented towards the treadmill (located in the centre of the figure).

In addition to the hardware, the motion capture system used requires the Simi Motion v.9.2.2. software (Simi Reality Motion Systems GmbH, Germany) for its operation, with tasks such as; calibration of the recording volume, recording of the running gesture, semi-automatic tracking of the reflective anatomical markers, and processing of the tracking data.

Preceding the capture of the running gesture and the processing of the tracking data, it was necessary to calibrate the cameras for the volume of recording. A T-wand and an L-frame were used to generate a valid 3D calibration, **Figure 26**. The T-wand is used to define the metric volume of the capture environment. The L-frame provides two rods of different lengths, the long rod defines the Y-axis and the short rod defines the X-axis. The Z-axis is defined perpendicular to the Y- and X-axis. This calibration will define the capture volume and a reference system for the measurements (global coordinate system).

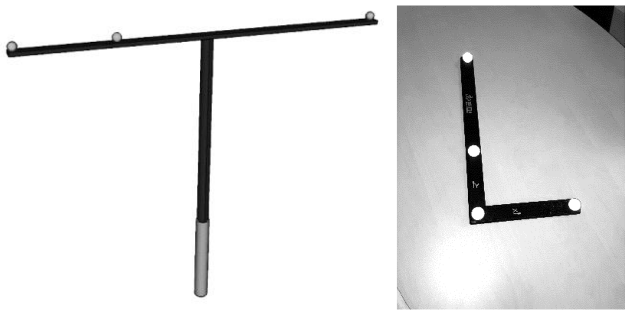


Figure 26. Tools for 3D calibration of the capture area. Left: T-wand. Right: L-frame.

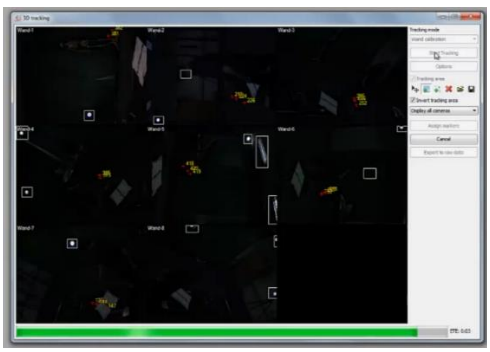


Figure 27. Screenshot of the automatic tracking process of the calibration tools by the Simi Motion software.

MARKER-SET AND TRACKING DATA PROCESSING

The 28 anatomical reflective markers placed on the skin of the participants defined the marker-set (**Figure 28**), with the aim of generating the different body segments of interest for the Doctoral Thesis in a three-dimensional environment with which to calculate the variables of interest.

Firstly, once the motion capture during the treadmill running protocol (described above) has been performed, the aim was to proceed to the analysis of the recorded videos. To do this, we proceeded to the semi-automatic tracking of the markers in the different recordings (static, comfortable speed and high speed) from the Simi Motion software, **Figure 29**.

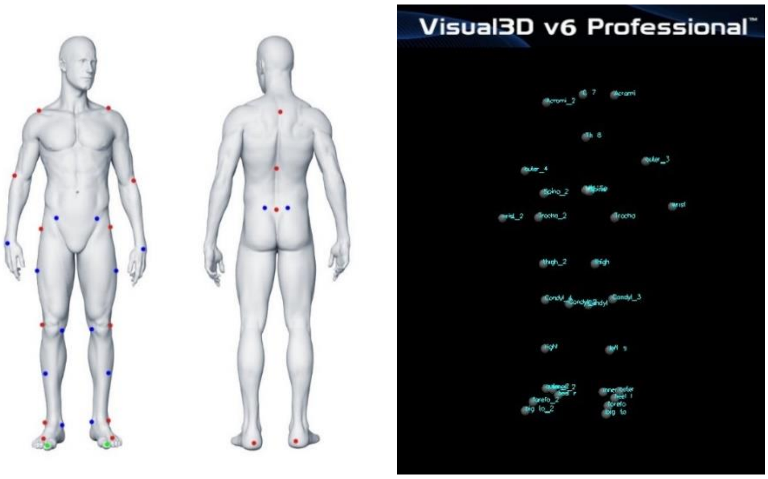


Figure 28. Graphical representation of the model by Simi Motion software on the left. Labels used to name each anatomical reflective marker in Visual3D Professional software on the right.

Secondly, after the semi-automatic tracking and review by the author of this Doctoral Thesis, the signals of the tracking data were processed in two steps, using Visual3D Professional software (v6; C-Motion, Rockville, MD):

1. A spline interpolation of 10% of the sampling frequency (286). Therefore, since the video recordings sampling rate was 100 frames per second, those gaps in the

raw tracking data of 10 or less frames, due to trajectory data loss during the semi-automatic tracking process, were estimated. A spline interpolation is a mathematical method for estimating missing data based on the range of a known discrete data set (287).

2. With the interpolated raw tracking data, a fourth-order Butterworth low-pass filter with a cut-off frequency of 8 hz was applied (120). The purpose is to smooth the raw tracking signal of markers placed on the skin that are affected by disturbance or vibrations caused by foot impacts against the ground and skin movements during running.

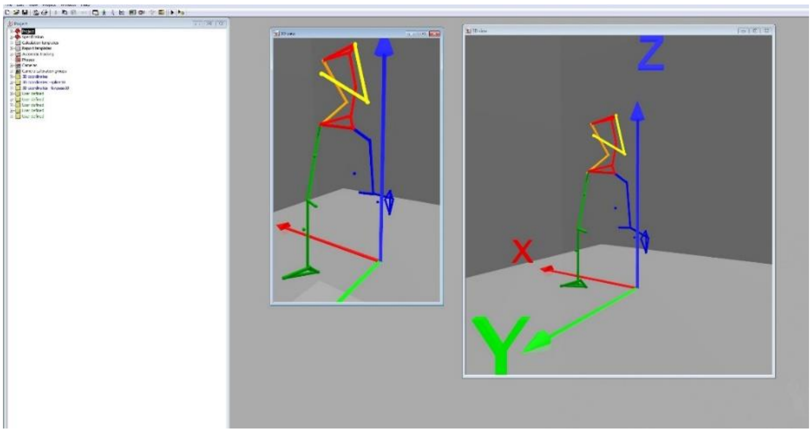
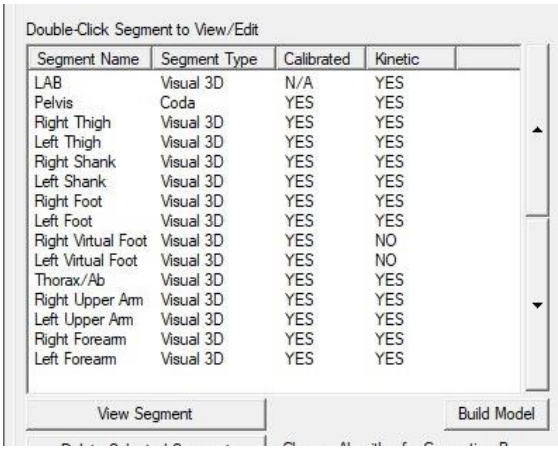


Figure 29. Screenshot of the Simi Motion software with the stick diagram of the raw data after semi-automatic tracking of the marker trajectories.

MODELLING AND DEFINITION OF BODY SEGMENTS

The Visual 3D Professional software (v6; C-Motion, Rockville, MD) was used to calculate the 3D kinematic variables of the running recording.

A total of 8 body segments were defined and created based on the processed trajectory data. The static test record mentioned above is used for this purpose. The 8 body segments used for this Doctoral Thesis were; foot (left and right), calf (left and right), thigh (left and right), pelvis and trunk, **Figure 30**. In addition, arm and forearm were defined, but have not been used for the analysis and results for this Doctoral Thesis.


Double-Click Segment to View/Edit

Segment Name	Segment Type	Calibrated	Kinetic
LAB	Visual 3D	N/A	YES
Pelvis	Coda	YES	YES
Right Thigh	Visual 3D	YES	YES
Left Thigh	Visual 3D	YES	YES
Right Shank	Visual 3D	YES	YES
Left Shank	Visual 3D	YES	YES
Right Foot	Visual 3D	YES	YES
Left Foot	Visual 3D	YES	YES
Right Virtual Foot	Visual 3D	YES	NO
Left Virtual Foot	Visual 3D	YES	NO
Thorax/Ab	Visual 3D	YES	YES
Right Upper Arm	Visual 3D	YES	YES
Left Upper Arm	Visual 3D	YES	YES
Right Forearm	Visual 3D	YES	YES
Left Forearm	Visual 3D	YES	YES

View Segment
Build Model

Figure 30. List of body segments created in Visual3D Professional.

The anatomical calibration system technique (CAST) was used to model each of the body segments mentioned above. This technique allows defining the movement of each segment in the six degrees of freedom (DOF), although only one plane will be used in this doctoral thesis. Also, it allows to define a local coordinate system by body segment, **Figure 31**.

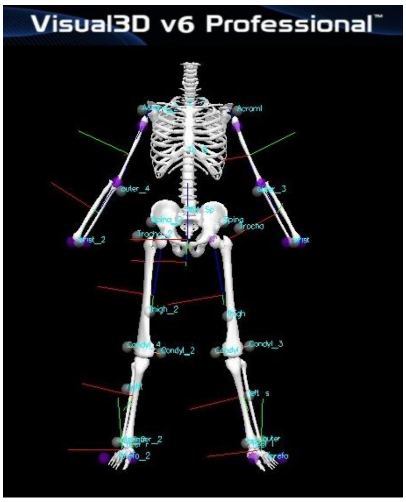


Figure 31. Screenshot of the modelling in Visual3D Professional. It shows the body segments, the markers with their labels and the local coordinate system of each segment.

The CAST technique is based on the identification of anatomical points through epidermal palpation of proximal-distal and medial-lateral areas of each segment. Hence, a total of at least four markers defines each segment. In addition, a fifth secondary marker per segment was used in case one of the four main markers was hidden, even after applying spline interpolation over the gaps. The segments foot, calf, thigh, pelvis and trunk are depicted in **Figure 32**.

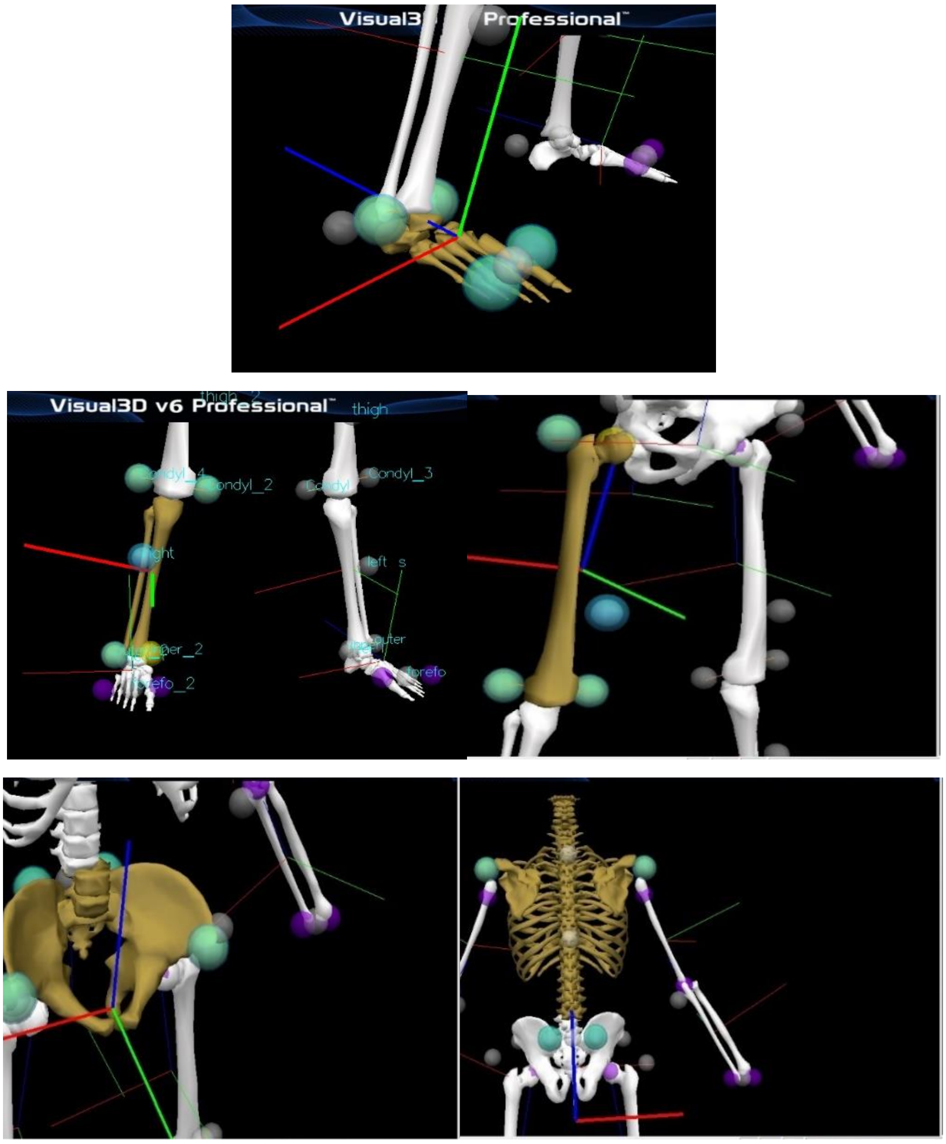


Figure 32. Graphical representation of each modelled segment. Four main markers for the CAST technique (light turquoise). Local coordinate system represented with a red vector for the X-axis, a green vector for the Y-axis and a blue vector for the Z-axis.

EVENT DETERMINATION

The algorithms of Handsaker et al. (288) were applied in this Doctoral Thesis to obtain the footstrike and take-off events during the running test, useful for determining the contact and flight phase of running.

Handsaker et al. (288) aimed to examine the accuracy of four algorithms based on running kinematics for estimating footstrike and foot toe-off events at different running speeds and stride types. To do this, the authors used a force platform (1000 Hz sampling rate) at a series of speeds synchronised with a 3D motion capture system (250 Hz sampling rate) to obtain the running kinematics. The algorithms were fed with acceleration and jerk signals from different foot markers to estimate landing (tested with 2 different algorithms), foot take-off (tested with 2 different algorithms).

In addition, they used the contact time measured through the force platform (goal standard), to be compared with the contact time measured through the 4 different algorithms to identify which one is more accurate.

Hence, based on Handsaker et al. (288) findings, the following algorithms were used for the event determination during running using kinematics data;

- Footstrike event, **Figure 33**: The peak vertical acceleration of the calcaneal marker was used if the support is RFS. And if the support was FFS, the vertical acceleration peak of the marker placed at 2-3 metatarsal head was used. For MFS, the marker that first generated the vertical acceleration peak was used, whether the marker was placed on the calcaneus or on the 2-3 metatarsal head.
- Take-off event, **Figure 34**: The vertical jerk peak of the 2-3 metatarsal head marker was used.

Acceleration formula

$$a = \frac{\Delta \mathrm{v}}{\Delta \mathrm{t}}$$

Jerk formula

$$\mathrm{j} = \frac{\Delta \mathrm{a}}{\Delta \mathrm{t}}$$

All the events mentioned in this section were calculated and supervised by the author of this Doctoral Thesis, who also used the videos recorded with Simi Motion's visible range cameras to verify that there were no possible errors.

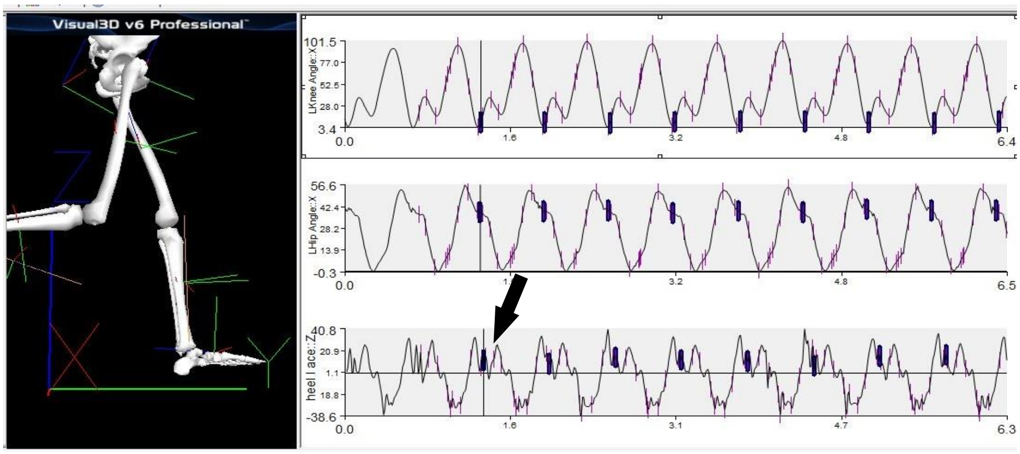


Figure 33. Screenshot from Visual3D Professional showing the footstrike event (the dark blue mark where the black arrow indicates) in the lower plot. This event is repeated cyclically at each step. Also shown is a comparison with hip flexion-extension (top plot) and knee flexion-extension (middle plot).

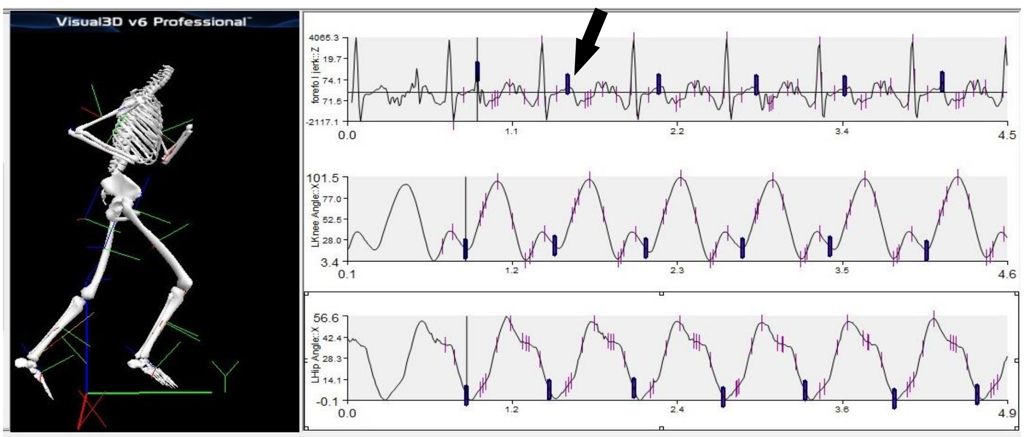


Figure 34. Screenshot from Visual3D Professional showing the take-off event (the dark blue mark where the black arrow indicates) in the top plot. This event is repeated cyclically at each step. Also shown is a comparison with hip flexion-extension (bottom plot) and knee flexion-extension (middle plot).

Of note, in order to determine the peaks following the recommendations of Handsaker et al. (288), based on acceleration and jerk, it was first necessary to determine a time window based on kinematic data. The reason is that the vertical acceleration and vertical jerk signals suggested by the scientific literature show numerous peaks, and precisely for neither the footstrike nor the take-off were the maximum peaks See **Figure 36** and **Figure 37**.

To determine this time window, pre-footstrike or pre-take-off and post-footstrike or post-take-off events were needed. These events used knee flexion-extension as their maximum flexion and extension values are very accurate in running for the sagittal plane, X. In addition, a close relationship to the footstrike and take-off events validated by Handsaker et al. (288) was observed.

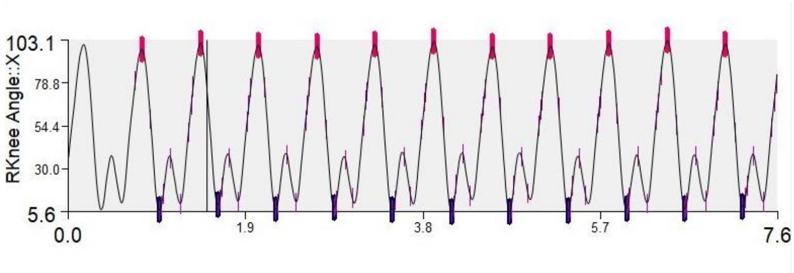


Figure 35. Plot of the flexion-extension angle of the right knee. Maximum knee flexion (red and top mark). Maximum knee extension (blue and bottom mark).

Specifically, to determine the beginning of the temporal window of the footstrike event, the maximum peak of knee extension of the same leg was used, since a few milliseconds before the footstrike runners present a knee in maximum extension. And for the end of this time window, the peak of maximum knee flexion of the opposite leg was used, which is in swing phase and occurs after and close to the footstrike (**Figure 36**).

And to determine the beginning of the time window of the take-off event, the maximum peak of knee flexion of the opposite leg was used, since the opposite leg is in swing phase, and it always happens before the take-off of the leg we are analysing. And for the end of this time window, we used the peak of maximum knee extension of the opposite leg, which occurs after the footstrike of the opposite leg after the take-off of the leg we are analysing (**Figure 37**).

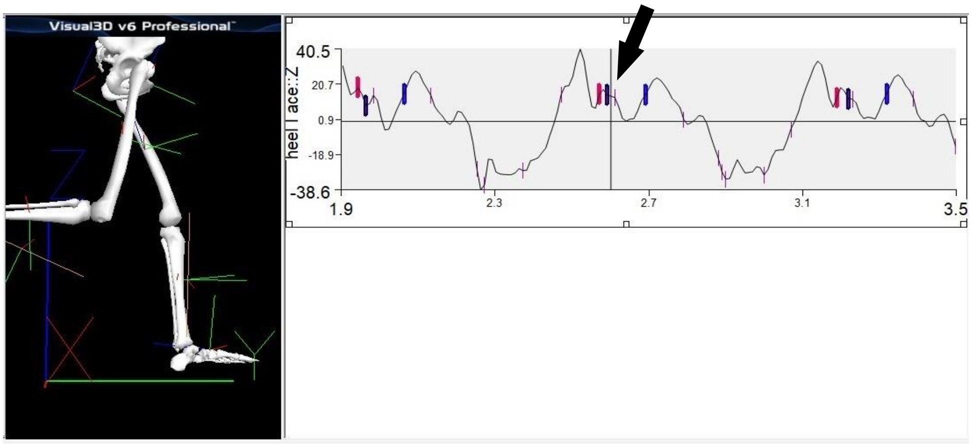


Figure 36. Screenshot from Visual3D Professional showing the footstrike event (dark blue mark marked by a black arrow) of a left rearfoot strike on a plot of the vertical acceleration of the calcaneus marker. The footstrike event is between the peak maximum knee extension of the left or same leg (red mark) and the peak maximum knee flexion of the right or opposite leg (light blue mark).

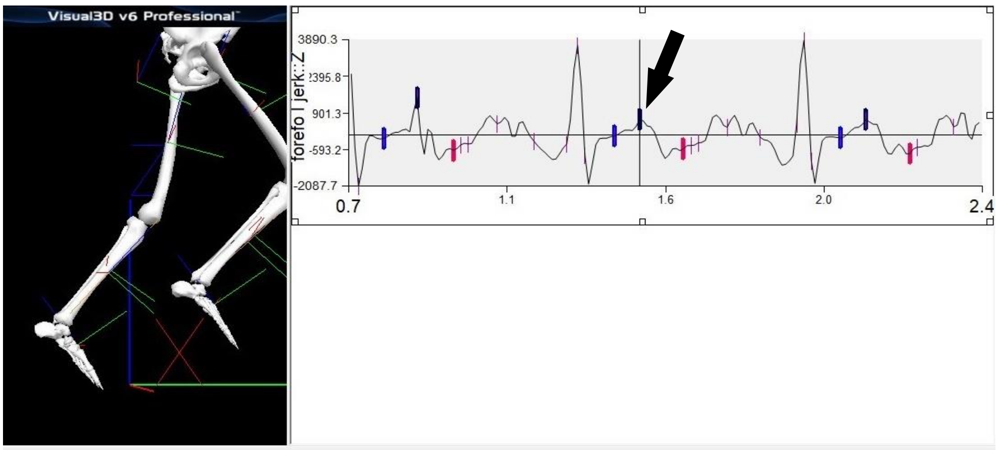


Figure 37. Screenshot from Visual3D Professional showing the take-off event (dark blue mark marked by a black arrow) of a left leg on a plot of the vertical jerk of the 2-3 metatarsal head marker. The take-off event is between the peak maximum knee flexion of the left or opposite leg (light blue mark) and the peak maximum knee extension of the left or opposite leg (red mark).

THREE-DIMENSIONAL ANGULAR KINEMATIC VARIABLES CALCULATION

Once the body segments under study had been modelled as rigid segments with their local coordinate systems (based on the static record), the three-dimensional kinematic running variables were calculated.

The joints of interest for this Doctoral Thesis are focused on the lower limbs, therefore, they were the ankle, knee and hip. The term "joint" can be used in different ways in Visual3D software. However, in this doctoral thesis, the focus is on the union or junction of two rigid segments from zero to six DOF. Hence, to create the ankle, knee and hip joints, the foot, shank, thigh, and pelvis segments were needed.

This union or junction between rigids segments needs a centre of union, in other words, an origin, **Figure 38**. This is known as the joint centre, which for the three joints under study was defined as follows:

- For the left and right ankles and knees, the midpoint of the distance between the two medial and lateral markers of each joint was used. The ankles were defined by the medial and lateral malleolus, and the knees by the medial and lateral epicondyle.
- The hip followed another algorithm. For this joint it is important to mention how the pelvis is modelled. Since, from this segment a virtual landmark marker is obtained (not obtained through a landmark marker by epidermal palpation). The CODA method (289) was used to model the pelvis, **Figure 39**. This method uses the following four anatomical reference markers; left and right anterior superior iliac spine (ASIS) and left and right posterior superior iliac spine (PSIS). Once the pelvis was created using the CODA method, the right and left hip joint centres were estimated using the following equations by Visual3D software:
    - (0.36 * ASIS_Distance, -0.19 * ASIS_Distance, -0.3 * ASIS_Distance) for the right hip joint centre.
    - (-0.36 * ASIS_Distance, -0.19 * ASIS_Distance, -0.3 * ASIS_Distance) for the left hip joint centre

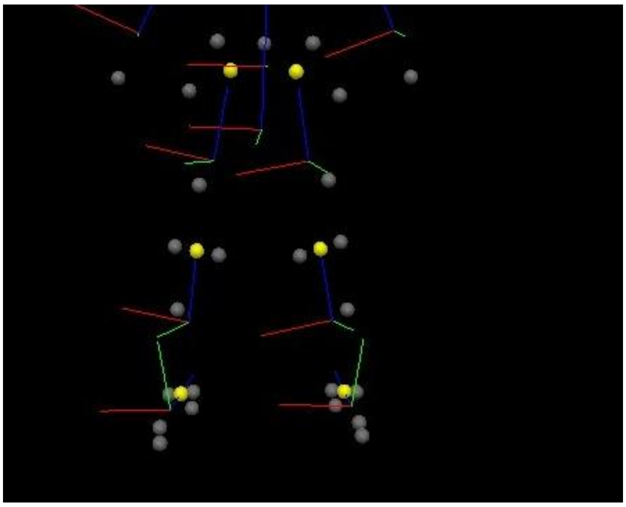


Figure 38. Representation of the ankle, knee and hip joint centres (circled).

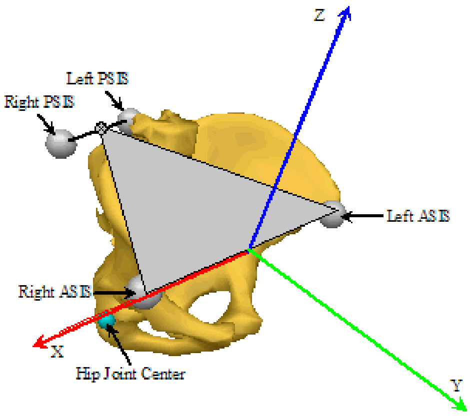


Figure 39. Graphical representation for hip joint centre estimation using CODA modelling of the pelvis. Image extracted from C-Motion Wiki Documentation for Visual3D software (290).

To define each joint, it is necessary to name a distal segment and a proximal segment, also known as a reference segment. See **Table 6** for the joints under study.

Table 6. Segment allocation for the creation of the lower limb joints used.

Joint	Distal Segment	Reference Segment
Left hip	Left thigh	Pelvis
Right hip	Right thigh	Pelvis
Left knee	Left shank	Left thigh
Right knee	Right shank	Right thigh
Left ankle	Left foot	Left shank
Right ankle	Right foot	Right shank

Another group of variables of interest in addition to the joints were the segments, where the angular kinematics of the foot, pelvis and trunk were also calculated for the sagittal plane.

To evaluate the angular kinematics of segments requires the interaction of two elements in a slightly similar way as the angular kinematics of joints is calculated in relation to the interaction between two rigid segments. The difference was that for the segments, the segment to be evaluated was used as the distal segment, and for the reference segment, the global or laboratory coordinate system was used (282). The global coordinate system was established with the L-frame during the calibration process, placed on the surface of the treadmill where the participants ran (mentioned above).

To determine the orientation of the angular kinematics of the segments and angles, the Cardan/Euler sequence of X, Y and Z was established, Recommended for the field of human biomechanics. Hence, it is assumed that the sagittal plane is the X-axis, the frontal plane is the Y-axis, and the transverse plane is the Z-axis.

However, for this doctoral thesis only the sagittal plane was used for the aforementioned regions of interest. Therefore, the variables used were the angles and angular velocities of the lower limb joints and the angles of the foot, pelvis, and trunk segments for the sagittal plane. The directions of each variable are defined in **Table 7**.

Table 7. List of angular kinematic variables with movement directions.

	Variable	Movement direction
Joints	Ankle angle / angular velocity	+ Dorsiflexion
		- Plantarflexion
	Knee angle / angular velocity	+ Flexion
		- Extension
	Hip angle / angular velocity	+ Flexion
		- Extension
Segments	Foot angle	+ Dorsiflexion
		- Plantarflexion
	Pelvis angle	+ Anterior tilt
		- Posterior tilt
	Trunk angle	+ Anterior tilt
		- Posterior tilt

THREE-DIMENSIONAL ANGULAR KINEMATIC VARIABLES FOR STATISTICAL ANALYSIS

For each of the variables (joints and segments) mentioned above was normalised for the running cycle using the footstrike event as the start. Average and standard deviation was calculated for each variable mentioned with each participant.

Then, to obtain the variables for the statistical analysis, the maximum and minimum peaks of the joints and segments mentioned above were obtained. Event determination (footstrike and take-off) was used to divide the peaks by running phases (stance phase and flight phase).

The angular variables of both joints and segments are then listed in **Table 8** with their respective graphical representation using an example participant in **Figure 40** (joint angles) and **Figure 41** (segment angles). Likewise, the list of angular velocity variables of the joints can be seen in **Table 9**, and their graphical representation using an example participant in **Figure 42**.

Table 8. List of angular variables for statistical analysis. Unit of measurement; degrees.

Phase	**Joint/segment**	**Description**
Stance phase	Foot	At footstrike
	Ankle	At footstrike
		Early plantarflexion after footstrike
		Peak dorsiflexion midstance
	Knee	Footstrike
		Peak flexion midstance
		Peak extension after midstance
	Hip	At footstrike
		Peak flexion midstance
		Peak extension after midstance
Flight Phase	Ankle	Peak plantar flexion after take-off
		Peak dorsiflexion before footstrike
	Knee	Peak flexion after take-off
		Peak extension before footstrike
	Hip	Peak flexion after take-off
Full cycle	Pelvis	Maximum anterior tilt
		Minimum anterior tilt
		Range of movement
	Trunk	Maximum anterior tilt
		Minimum anterior tilt
		Range of movement

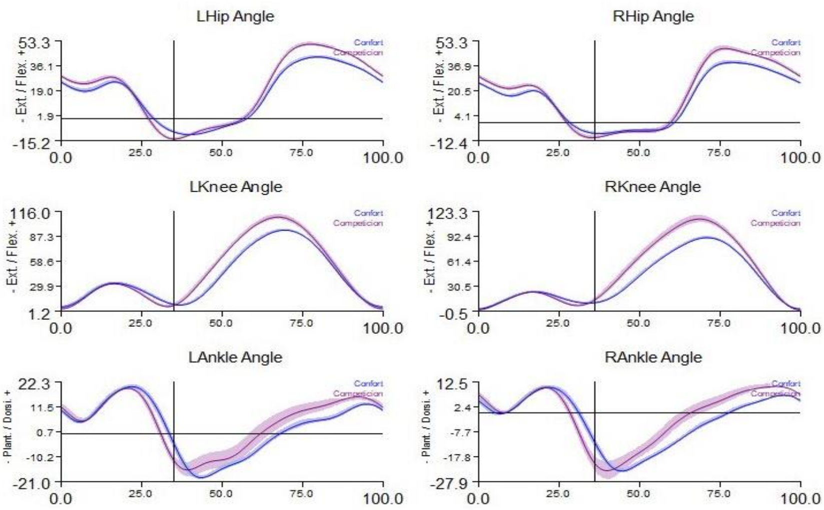


Figure 40. Plots with mean and standard deviation of an example participant for hip (top plots), knee (middle plots) and ankle (bottom plots) angles. LHip; Left hip. LKnee; left knee. LAnkle; left ankle. RHip; Right hip. RKnee; right knee. RAnkle; Right ankle.

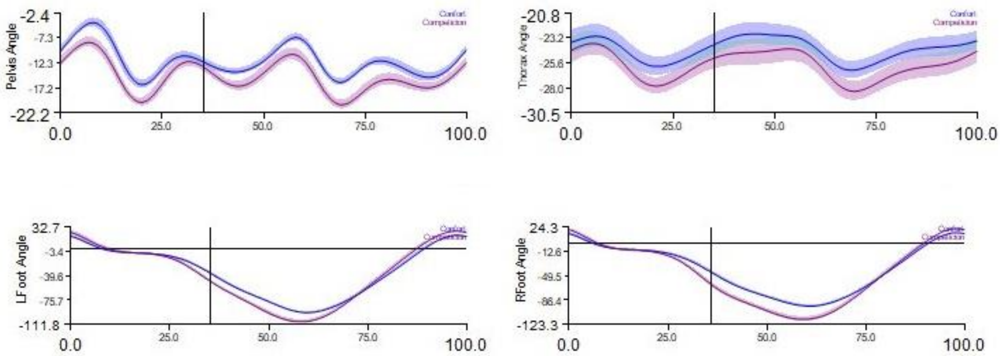


Figure 41. Plots with mean and standard deviation of an example participant for pelvis (top left plot), trunk (top right plot), left foot (bottom left plot) and right foot (bottom right plot). LFoot; Left foot. RFoot; Right foot.

Table 9. List of angular velocities variables for statistical analysis. Unit of measurement; degrees/second.

Phase	**Joint**	**Description**
Stance phase	Ankle	Peak dorsiflexion after footstrike
		Peak plantarflexion before take-off
	Knee	Peak flexion after footstrike
		Peak flexion before take-off
	Hip	Peak flexion after footstrike
		Peak extension before take-off
Flight Phase	Ankle	Peak dorsiflexion before footstrike
	Knee	Peak flexion after take-off
		Peak extension before footstrike
	Hip	Peak flexion after take-off

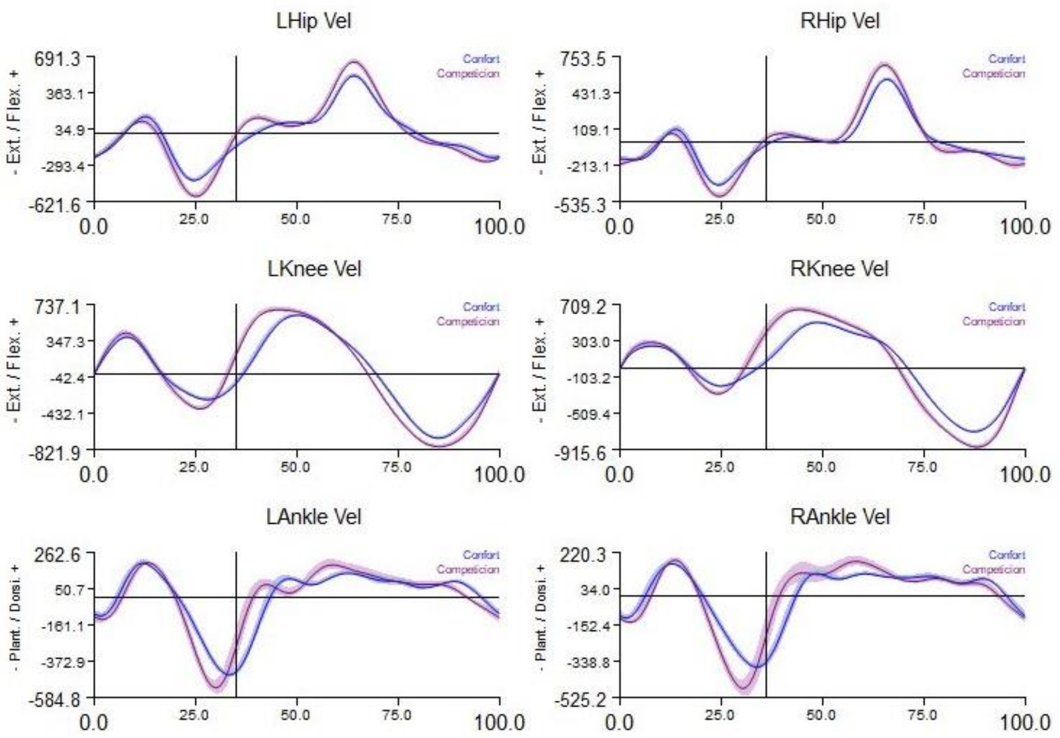


Figure 42. Plots with mean and standard deviation of an example participant for hip (top plots), knee (middle plots) and ankle (bottom plots) angles velocities. LHip; Left hip. LKnee; left knee. LAnkle; left ankle. RHip; Right hip. RKnee; right knee. RAnkle; Right ankle. Vel; Angular velocity.

Of note, the three-dimensional movement recordings had a duration of 15 seconds, thus allowing the average of each of these cycles to be calculated with at least 40 steps in total (both left and right).

In addition, for the interpretation of the type of footprint based on the foot to footstrike angle (FSA) it was established (282):

- **Rearfoot strike (RFS)**: FSA greater than 8.0°.
- **Midfoot strike (MFS)**: FSA from 8.0° to -1.6°.
- **Forefoot strike (FFS)**: FSA less than -1.6°.

3.6. STATISTICAL ANALYSIS

For this doctoral thesis different statistical techniques have been used, most of them to evaluate the differences between groups and the association/correlation between variables.

Prior to the statistical analysis, the normality of the variables was assessed using different graphs and tests: 1) Frequency histograms and Q-Q plots. 2) Mean-median ratio between 0.95 and 1.05. 3) Kolmogorov-Smirnov normality test. 4) Levene's tests. And 5) Shapiro-Wilk normality test. Mean, standard deviation, frequency and percentage were used as descriptive values.

To analyse the differences between quantitative, a 3x2 analysis of variance with repeated measures (ANOVA), and analysis of covariance (ANCOVA) were used. Only for the ANOVA, paired t-tests were used as post-hoc tests when a significant interaction between groups and time was detected.

To analyse the differences between nominal variables McNemar's test were used.

Intra-observer and inter-observer reliability were calculated using Cohen's Kappa and proportion of agreement for footstrike pattern and inversion **(Study 1)**.

Effect sizes for group differences were expressed as Cohen's *d* (291); effect sizes are reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) (291).

Regarding the rearfoot strike (RFS) prevalence, a chi-squared (χ^2) test was used to compare the differences between groups.

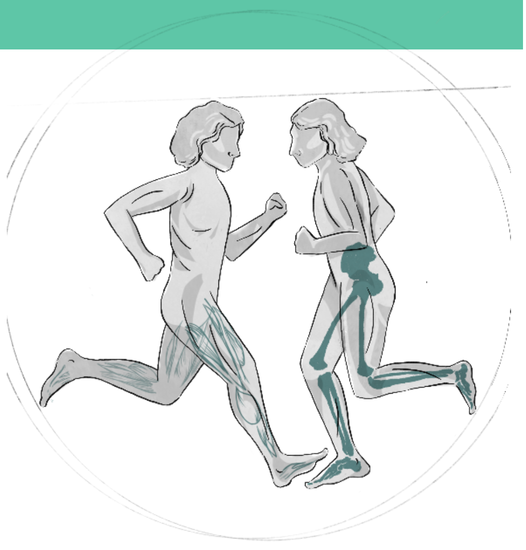
To verify that there were no differences between groups at baseline, a one-way ANOVA was used for continuous variables and a chi-square test (χ2) was used for the sex variable (dichotomous).

The following parameters were selected for a priori sample size calculation for **SECTION 2 (studies 2, 3 and 4)**: moderate effect size f = 0.252, α level of 0.05, a power level of 0.95, Noncentrality parameter λ = 16.500, critical F = 3.142.

The software used for data analysis and statistical analysis were:

- SPSS for Windows (IBM, Chicago, USA): Statistical analysis software.
- G*Power: Software used for a priori sample size calculation.

CHAPTER 4. RESULTS AND DISCUSSION



SECTION 1. BIOMECHANICAL RUNNING ASSESSMENT IN A REAL COMPETITION SITUATION.

STUDY 1. DOES FATIGUE AFFECT THE KINEMATICS OF ENDURANCE RUNNING?

STUDY 1

Does fatigue affect the kinematics of endurance running?

¿Afecta la fatiga a la cinemática de la carrera de resistencia?

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Abstract

The purpose of this study was to determine the footstrike pattern (FSP), inversion (INV) and spatial-temporal variables in a large sample of recreational runners during a long-distance competition, according to sex and changes in the classification race. A total of 368 men and 67 women, who participated in the XVII International Half Marathon of Cordoba (Spain) were analysed. It was recorded at km 5 and km 15, where high-speed camcorder and 2D-photogrammetric techniques were used to measure FSP, INV, contact time (CT) and flight time (FT). The group that worsened their classification at km 15 increase RFS prevalence and INV asymmetry. A Pearson analysis indicates that variation of the classification in the race between the marks km 5 and km 15 is related with CT ($r=0.429$, $p<0.001$) and FT ($r=-0.360$, $p<0.001$). RFS prevalence and spatial-temporal parameters showed different patterns depending on whether the runners improved or worsened their ranking.

Keywords: running; long distance; endurance; biomechanics; performance.

Resumen

El objetivo de este estudio fue determinar el patrón de pisada, inversión y variables espaciotemporales para una amplia muestra de corredores amateurs, durante una carrera de larga distancia, según sexo y posición de clasificación. Se analizaron 368 hombres y 67 mujeres, que participaron en la XVII Media Maratón Internacional de Córdoba (España). Se registró el km 5 y km 15, utilizando técnicas de fotogrametría 2D de alta velocidad para medir la pisada, la inversión, el tiempo de contacto (TC) y el tiempo de vuelo (TV). El grupo que empeoró su clasificación en el km 15 aumentó la prevalencia de FSP y la asimetría del INV. Un análisis de Pearson indica que la variación de la clasificación en la carrera está relacionada con TC ($r=0.429$, $p<0.001$) y TV ($r=-0.360$, $p<0.001$). La prevalencia de retropié y los parámetros espaciotemporales mostraron diferentes patrones dependiendo de si los corredores mejoraron o empeoraron su clasificación.

Palabras clave: carrera; larga distancia; resistencia; biomecánica; rendimiento.

Introduction

Running as an activity to improve health and personal performance has become increasingly widespread among the recreational population. Today, the number of participants in popular endurance races has increased, along with the number of organised running races. For instance, in the half marathon of Valencia 2020, Spain, 19,076 runners (19.51% women) finished the race. The popular phenomenon of running is due, among other factors, to the satisfaction of physical and psychological health needs, goal achievement, tangible rewards, social influences, and easy availability (8,9). Advances in the description of the physiological, psychological and especially biomechanical characteristics of these runners is necessary in term of injury prevention and performance improvement. In this context, the spatiotemporal gait parameters such as: contact time (CT), flight time (FT), step frequency, kinematics parameters such as: foot strike patterns (FSPs) and kinetics variables such as: impact loading rate, ground reaction force, etc., have been widely studied, although with controversial results (292).

Today, runners sustain injuries at a high rate: Despite the scientific and technological advances around running, training control, technique or footwear, between 27% and 70% of recreational and competitive distance runners are injured during any period of the year (18,21,293). The etiology of these injuries is multifactorial. Several intrinsic and extrinsic factors have been implicated as risk factors of lower extremity injury, for instance: 1) age, sex, physical fitness, anatomic misalignments; and 2) body mass index, previous injury, inadequate rehabilitation, level of competition, number of weekly sessions of training, shoe type, running surface, respectively (21,294–297).

However, there is controversial debate regarding what are the most important factors of injury risks for runners. Issues related to risk factors and optimal FSP are the subject of prominent discussion, such as, for example, the dynamics of the foot in contact with the ground, and the ideal running shoes (298). Recently, Kulmala et al. (299) found that highly cushioned shoes increase leg stiffness, impact loading and change the spring-like mechanics of running in athletes who run with rearfoot strike (RFS). In turn, running in conventional and maximalist footwear may increase demands on the musculoskeletal structures to reduce impact transients, which may be detrimental to passive tissues. Therefore, running with cushioned shoes influences injury risk in recreational runners overall (300). In addition, modern running shoes have altered our FSP from a predominantly forefoot strike (FFS), landing with the ball of the foot to a predominantly RFS, landing with the half or rear third part of the sole only (158). Consequently, the sudden force of loading is distributed across the runner's musculoskeletal system, making FSP a significant predictor of injuries (18,133,230,301). In this regard, although running with FFS seems to be a characteristic of human evolution (18), adult amateur endurance runners exhibit a high prevalence — between 74.9% and 95.4% — of RFS (62,84,96,103). RFS is associated with higher vertical loading, ankle stiffness and knee stiffness (133), and some previous studies have suggested its association with injury risk (18,85). Lieberman et al. found higher force collision at foot-strike on RFS than midfoot strike (MFS) and FFS (85). According to several studies, RFS and FFS usually have different patterns of ground reaction force; RFS landings generate a rapid and high-impact peak in the ground reaction force, just after foot strike against the ground; FFS also generates an impact, although there is not a clear and accentuated impact peak (85,117,118).

The use of the different FSPs also depends on the running speed, running surface, fatigue (18) and runners' levels (62). In particular, an FFS may become difficult to maintain in longer endurance events (302). Accordingly, Ogueta-Alday et al. (83) note that among long-distance runners there is a relationship between athletic level in the half marathon and the type of FSP; in this sense, high-level runners showed the highest percentage of MFS/FFS (~ 73%) and a lower CT compared to the other three lower-level groups. The increase in CT shows a strong relationship with the increase in step length during a run to exhaustion at VO2max speed. Consequently, the ability to maintain a short ground CT appears to be absolutely necessary to maintaining performance during a run to exhaustion (303). In addition, a shorter CT with inversion at the initial foot contact allows the use of elastic energy and stiffness of the leg muscle to increase running economy (84). However, Latorre-Román et al. (304) indicated that there were no significant changes in the kinematics [CT and FT] and FSP characteristics in endurance runners after fatigue induced by a long high-intensity intermittent training (HIIT) consisting of 5x2000 m with 120 s recovery between runs and high fatigue levels. Likewise, García-Pinillos et al. (305) report that neither athletic performance nor exhaustion level reached seems to be determinant in the kinematic variables such as CT, FT and step length and FSP response during a HIIT consisting of 4×3×400 m repeats with a passive recovery period of 1 minute between runs and 3 minutes between sets.

Therefore, despite numerous studies trying to define the advantages and disadvantages of certain foot-striking patterns and footwear (96), few studies have been conducted regarding FSPs in large samples of recreational runners during a long-distance race competition (62,84,96). The disadvantage of these studies is that they did not carry out an intra-participant analysis during the race. Consequently, little is known about the evolution of FSP and kinematic variables during a long-distance race through measures in several marks of the race in recreational runners. Recently, Bovalino et al. (106) and Larson et al. (103) showed that a large percentage of runners modified their FSP from non-RFS to RFS, from the initial phase to the later phase of the race. However, these studies did not analyze the effect of changes in the classification of the runners during the race on kinematic variables, i.e. intra-participant differences.

Considering the above information, this study focused on fatigue-induced changes on kinematic parameters in recreational long-distance runners. Therefore, the purpose of this study was to determine FSP, inversion and spatial-temporal variables in a large sample of mostly recreational runners during a long-distance road competition, according to sex and changes in the classification during the race between two kilometric marks (km 5−km 15).

Materials and methods

Participants

Four hundred thirty-five athletes (368 men and 67 women) who participated in the XVII International Half Marathon of Cordoba (Spain) were analyzed. The runners were recorded at two different kilometer marks over the course of the race: km 5 and km 15. These localisations were chosen by considering the space between athletes (i.e. avoiding the crowd at the start) and the lack and presence of fatigue in km 5 and km 15 marks, respectively. The study was approved by the ethics committee of the University of Jaen.

Procedures

Sagittal plane videos (240 Hz) were recorded using a high-speed camcorder (Casio Exilim EXF1, Shibuyaku, Tokyo 151–8543, Japan) at km 5 and km 15. Videos were taken from a lateral view, with the camera perpendicularly placed 5 meters from the participant so that they could be filmed in the sagittal plane. The filming location was set along a 5-meter corridor. Video data were analyzed using a 2D video editor (VideoSpeed vs1.38, Granada, Spain). The 2D video-based determination of the FSP has been used in other studies (115) and, despite not being as exact as the biomechanical determination, it is practical for the assessment of a large cohort (306) and is valid and highly reliable regardless of the experience of the assessor (307). The dependent variables selected for the kinematics analysis are in line with previous studies (84,103,308) and are as follows: FSP at first contact with the ground, from rearfoot to forefoot: RFS, where initial contact is made somewhere in the heel or back third of the foot; MFS, where the heel and sole make contact almost simultaneously; and FFS, where initial contact is made with the metatarsal heads. *Figure **43*** shows pictures that illustrate different FSPs. According to the procedure used in previous studies (115), the FSP was rated as RFS or non-RFS since this dichotomous variable shows very high accuracy in determining an RFS (inter-rater accordance: 0.981) and lower accuracy in deciding between an FFS and MFS (0.893) (115). In turn, the inversion (INV) in stance phase was observed in relation to rotation on the antero-posterior axis and was registered when the shoe contacts the ground in its lateral part. In addition, using 2D photogrammetric techniques, contact time (CT) (time for which the foot is in contact with the ground) and flight time (FT) (time during which there is no contact with the ground) were analyzed. Moreover, asymmetries between the right and the left foot were also analyzed. Filming locations, both at km 5 and km 15 marks were characterised by relatively flat ground surfaces so that FSP would not be influenced by incline or decline of ground surface. For each runner, approximately four acceptable foot strikes were captured on film (two right and two left).

Figure 43: Foot strike type and inversion of the foot. From left to right: Rearfoot strike, midfoot strike, forefoot strike, and inversion.

Statistical analyses

Descriptive statistics are represented as mean, standard deviation, frequency and percentage. To analyze the differences between quantitative and nominal variables, analysis of variance (ANOVA) and McNemar’s test were used, respectively. The average of both feet (left and right steps) was used for spatial-temporal variables. In addition, in a sample of 80 runners, intra-observer and inter-observer reliability were calculated using Cohen's Kappa and proportion of agreement for FSP and INV. These observations were performed by three experienced observers between the changes in the classification in the race between km 5 and km 15 marks and CT and FT. The level of significance was $p < 0.05$. Data analysis was performed using SPSS (version 21, SPSS Inc., Chicago, Ill, USA).

Results

The intra-observer reliability obtained for FSP was Kappa = 0.904 value and for inversion Kappa = 0.732 value. The inter-observer reliability obtained for FSP was Kappa = 0.801 ± 0.09 value, and for inversion Kappa = 0.727 ± 0.11 value. **Table 10** shows the proportion of agreement for FSP and inversion.

The classification in the race from km 5 to km 15 mark got worse both in men (187.51±109.11 vs. 210.71±119.56 rank, p<0.001) and women (385.44 ±63.88 vs. 450.89±71.59 rank, p<0.001). **Table 11** shows FSP, INV and the asymmetry for the whole group and regarding sex at km 5 and km 15 marks. In the total sample and in men there is a significant increase of RFS prevalence from km 5 to km 15 mark. However, women did not show significant changes. Likewise, INV asymmetry displayed the same behaviour. Taking into account the runners who improve (range Δ22.37) and worsen (range Δ46.27) their classification from km 5 to km 15 mark, **Table 12** shows that the group whose classification worsens at km 15-mark increases RFS prevalence and INV asymmetry. Moreover, significant differences were found in CT and FT both in men and in women (**Figure 44**). Women increased CT (p<0.001) and reduced FT (p<0.01) at km 15 mark. However, men increased FT (p<0.001) at km 15 mark. In addition, the runners who improved ranking at km 15 mark reduced CT (p<0.01) and increased FT (p<0.001) (**Figure 45**). The runners whose ranking worsened, increased CT (p<0.05). A Pearson correlation analysis indicated that variation of the classification in the race between km 5 and km 15 mark was related to CT (r=0.429, p<0.001) and FT (r=-0.360, p<0.001).

Table 10. Proportion of agreement for FSP and inversion (intra-observer)

	RFS	MFS	FFS	INV
RFS	88.66%			
MFS		83.3%		
FFS			100%	
INV				85%

RFS: rearfoot; MFS: midfoot; FFS: forefoot; INV: inversion.

Table 11. FSP, INV and the asymmetry according to the total sample and sex at km 5 and km 15 marks

	All				Men				Women			
	Km 5		Km 15		Km 5		Km 15		Km 5		Km 15	
	Left foot	Right foot	Left foot	Right foot	Left foot	Right foot	Left foot	Right foot	Left foot	Right foot	Left foot	Right foot
RFS	400 (92.0)	401 (92.2)	416 (96.1)***	412 (95.2)*	336 (91.3)	337 (91.6)	351 (9.9)***	349 (95.1)*	64 (95.5)	64 (95.5)	64 (95.5)	65 (97.0)
RFS asymmetry	17 (3.9)		17 (3.9)		15 (4.1)		13 (3.6)		2 (3.0)		4 (6.0)	
INV	210 (48.3)	210 (48.3)	215 (50.2)	214 (49.7)	193 (52.4)	190 (51.6)	210 (48.3)	210 (48.3)	215 (50.2)	214 (49.7)	193 (52.4)	190 (51.6)
INV asymmetry	30 (6.9)		50 (11.8)**		27 (7.3)		45 (12.6)**		3 (4.5)		5 (7.6)	

RFS: rearfoot strike; INV: inversion; *p<0.05, **p<0.01, p<0.001. Data is displayed as n (%).

Table 12. FSP, INV and the asymmetry according to the classification at km 5 and km 15 marks

	Runners who improved their ranking				Runners who worsened their ranking			
	Km 5		Km 15		Km 5		Km 15	
	Left foot	Right foot	Left foot	Right foot	Left foot	Right foot	Left foot	Right foot
RFS	94 (89.5)	93 (88.6)	98 (95.1)	97 (93.3)	306 (92.7)	308 (93.3)	318 (96.4)**	318 (96.4)*
RFS asymmetry	7 (6.7)		3 (2.9)		10 (3.0)		10 (3.0)	
INV	59 (56.2)	57 (54.3)	62 (60.2)	58 (56.3)	151 (45.8)	153 (46.4)	153 (47.1)	156 (47.6)
INV asymmetry	10 (9.5)		13 (12.9)		20 (6.1)		37 (11.5)**	

RFS: rearfoot strike; INV: inversion; *p<0.05, **p<0.01, p<0.001. Data is displayed as n (%).

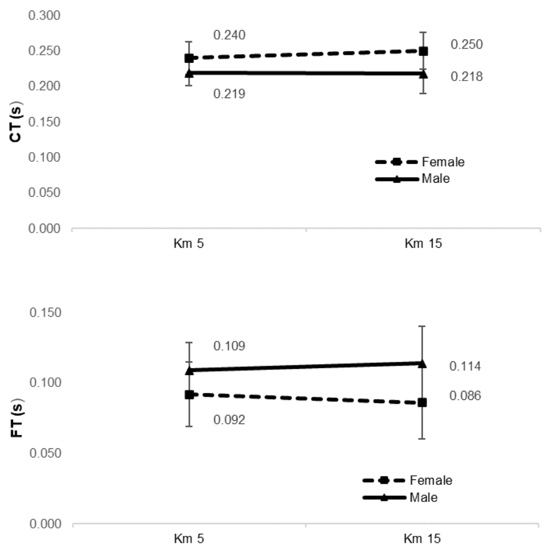

Figure 44. Contact time and flight time in men and women according to classification from km 5 to km 15 mark

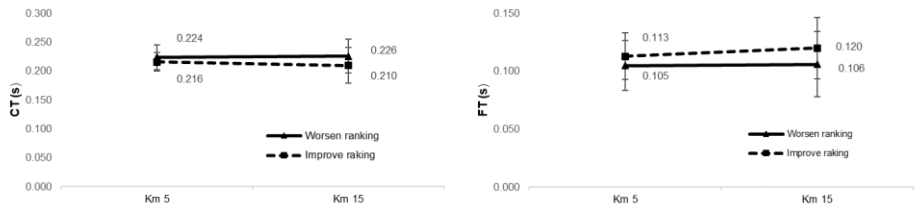

Figure 45. Contact time and flight time in the runners that worsened or improve their classification from km 5 to km 15 mark.

Discussion

The official website of the 2011 International Half Marathon of Cordoba reported that 3,124 athletes finished the competition; the fastest time for men was 1 h 05’08” and for women was 1 h 22’31”, with a mean time of 1 h 43’50”. This study population is representative of the current average- to long-distance runner. The purpose of this study was to determine FSP, inversion and spatiotemporal variables in a large sample of mostly recreational runners during a long-distance road competition, according to sex and changes in the classification during the race between two kilometric marks (km 5−km 15).

The main finding of this study was that there was an increase of RFS prevalence from km 5 to km 15 mark only in the men’s group. In addition, the runners whose classification worsened in the race at km 15 mark, displayed greater RFS prevalence and INV asymmetry. Regarding the spatial-temporal parameters, women increased and reduced CT and FT, respectively at km 15 mark. In addition, the runners who improved ranking at the km 15 mark reduced CT and increased FT and a positive and negative relationship was found between the variation of the classification in the race from the km 5 to the km 15 mark and CT and FT, respectively.

Although very few studies have investigated this topic, in accordance with the current study, Hanley at al. (105) showed that in elite marathon runners the most usual FSP was RFS, with proportions never less than 54% of men or 67% of women at any distance; moreover, the proportion of RFS increased during the race in the men, although more than 75% of athletes kept their FSP. In this regard, a recent study noted that of the runners that use a non-RFS early, a large proportion change to RFS as distance increases (106). FFS presents greater muscle activity in medial and lateral gastrocnemius compared to RFS (309), over the course of a competition, accumulated fatigue may reduce the number of FFS. Likewise, Hasegawa et al. (84) noted an increase in RFS frequency in relation to the worst positions in the competition. In turn, Larson et al. (103) found an increase in RFS frequency between the km 10 and km 32 of an international marathon, presumably due to fatigue; however, foot asymmetry was less common at km 32. A recent study observed no spatiotemporal asymmetries between dominant and non-dominant leg for recreational runners (310). These findings in accordance with that noted change from FFS to MFS over an exhaustive run due to a muscular fatigue resulting from an increase in eccentric loading of the ankle plantar–flexor muscles at touchdown in forefoot runners, which may contribute to a decreased torque output by the end of the run (302). In an ultramarathon (161-km) (104), an increase in RFS prevalence by race midpoint due to higher muscular demands reflected in high concentration post-race blood creatine kinase concentrations among non-RFS. Likewise, Salas Sánchez et al. (296) in a laboratory setting, indicated that the frequency of RFS increases with fatigue. Therefore, the changing of FSP in long-distance runners may be due to compensating for neuromuscular fatigue because a reduced maximum voluntary contraction during plantar flexion of the ankle was observed after the race; although that does not indicate more efficiency in the race (292). In this context, RFS and MFS runners exhibit greater impact load than FFS over the course of a marathon. In addition, this impact load increases with speed for both RFS and MFS, but not FFS, although, both speed and impact load were reduced between the km 10 and km 40 race marks of the marathon (311). Recently, Bovalino et al. (106) reported an significant increase in RFS prevalence from km 3 to km 13 mark (76.9% vs. 91%, respectively) and that race completion time differed by FSP, where faster runners were more consistent with non-RFS than the slowest runners (62.64 ± 11.20 min vs. 72.58 ± 10.84 min; $p < 0.001$). These findings are according to a study by Hasegawa et al. (84) and Latorre-Román et al (62) who remark that the percentage of RFS increases with a decreasing running speed; consequently, RFS overall was more common among the slower population of runners.

In relation to sex, unlike men, women did not modify their FSP and INV, results similar to those of Larson et al. (103) between km 10 and km 32 marks of the marathon, who find a greater increase of RFS prevalence in men than women. In the elite marathon runners at the 2017 IAAF World Championships (105), showed that there were no sex differences for proportion of FSP. Although they found the proportion of RFS increased with distance run in the male runners, women did not exhibit differences between km 19 and km 40 marks in FSP. However, Kasmer et al. (104) found no significant differences between men and women in FSP and during a 161-km ultramarathon, considering several filming locations. Recently, Boccia et al. (312) indicated that a half-marathon run incited both central and peripheral fatigue, without significant differences between men and women. Therefore, this is a controversial topic or a knowledge gap in the field of study.

With respect to spatial and temporal variables, there were significant changes, both in CT and FT, from km 5 to km 15 mark, taking into account both sex and position in the race, men and the runners who improve rank at km 15 mark, reducing CT and increasing FT. These results differ from Chan-Roper et al. (313), who demonstrate increased CT between km 8 and km 40 of a marathon.

In this regard, longer FT and step length seem to be the main running characteristics of high-level runners compared to their low-level counterparts (314). Therefore, shorter CT seems to be very consistent among highly trained endurance runners (83). However, CT and FT presented contradictory results regarding their association with running economy in long-distance runners (315). Runners with RFS are more economical than those who exhibit MFS at submaximal running speeds (57%–81% of V̇O2max) and this difference could be explained due to CT being longer and FT shorter in runners with RFS (316). Consistent with this, a longer CT involved a lower V̇O2max in MFS and RFS; and at a given CT, RFS runners were less economical than MFS (317). Finally, a shorter CT and a higher frequency of INV at the foot contact might contribute to higher running economy (84).

Some limitations in this study must be mentioned. The main limitation of this study was not providing sociodemographic and anthropometric variables, which could have helped with the discussion. A second limitation is the use of a video analysis system to measure FSP, which is less accurate than a 3-D motion capture system. Thirdly, footwear was not controlled or assessed. Notwithstanding these limitations, the current study includes a large population sample of runners, so these results provide high statistical power. From a practical point of view, the results of the current study may be used to characterise typical running of recreational long-distance runners during a half marathon, which provides useful information for athletes and coaches to gain a better understanding of how the impact of FSP could influence the athlete's performance or injuries' risk. Significant differences between FSP and spatial-temporal parameters according to sex and changes in the position in the race, suggested by this study, make an original contribution to the biomechanical analysis of endurance running from an ecological paradigm (outside the laboratory). However, the current study cannot determine with precision whether more experienced well-trained runners, fatigue or pacing control are responsible for changes in FSP and of spatial-temporal parameters during the race.

Conclusions

There was a high prevalence of RFS among most recreational distance runners, which increased from km 5 to km 15 only in the men groups and in runners, whose classification worsened in the race at km 15. In turn, spatial-temporal parameters during a half marathon were affected by sex, with women increasing and reducing CT and FT, respectively, from km 5 to km 15 mark. In addition, the runners who improved their position in the race at km 15 mark reduced CT and increased FT. These findings suggest that maintaining a non-RFS, not increasing contact time, and not decreasing flight time could be beneficial in improving performance during a long-distance race in the last kilometers. Further research could clarify the causes and consequences of current findings on running performance and injuries.

SECTION 2. EFFECTIVENESS OF TWO RUNNING RETRAINING PROGRAMS FOR RECREATIONAL LONG-DISTANCE RUNNERS

STUDY 2. THE EFFECT OF TWO RETRAINING PROGRAMS, BAREFOOT RUNNING VERSUS INCREASING CADENCE: A RANDOMISED CONTROLLED TRIAL

STUDY 2

The effect of two retraining programs, barefoot running versus increasing cadence: a randomised controlled trial

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Abstract

The aim of this study was to compare the effects of two 10-week non-laboratory based running retraining programs on foot kinematics and spatiotemporal parameters in recreational runners. One hundred and three recreational runners (30 ± 7.2 years old, 39% females) were randomly assigned to either: a barefoot retraining group (BAR) with 3 sessions/week over 10 weeks, a cadence retraining group (CAD) who increased cadence by 10% again with 3 sessions/week over 10 weeks and a control group (CON) who did not perform any retraining. The footstrike pattern, footstrike angle (FSA) and spatial-temporal variables at comfortable and high speeds were measured using 2D/3D photogrammetry and a floor-based photocell system. A 3x2 ANOVA was used to compare between the groups and 2 time points. The FSA significantly reduced at the comfortable speed by 5.81° for BAR ($p < 0.001$; Cohen's d = 0.749) and 4.81° for CAD ($p = 0.002$; Cohen's d = 0.638), and at high speed by 6.54° for BAR ($p < 0.001$; Cohen's d = 0.753) and by 4.71° for CAD ($p = 0.001$; Cohen's d = 0.623). The cadence significantly increased by 2% in the CAD group ($p = 0.015$; Cohen's d = 0.344) at comfortable speed and the BAR group showed a 1.7% increase at high speed. BAR and CAD retraining programs showed a moderate effect for reducing FSA and rearfoot prevalence, and a small effect for increasing cadence. Both offer low-cost and feasible tools for gait modification within recreational runners in clinical scenarios.

Keywords: running form, gait retraining, step rate, metronome, unshod.

Introduction

Running as a recreational activity has been reported to improve health and personal performance. However, between 26% to 74% of recreational runners have been reported to suffer running related injuries each year (16–18), with an incidence of 30.1 injuries every 1,000 hours of running exposure (19). Despite scientific and technological advances in footwear, training load control and running technique, the incidence of running related injuries has not changed significantly over the last 20 years. Contrary to an evolutionary perspective where running with forefoot strike (FFS) seems to be a common feature (85), more than 90% of recreational runners present a rearfoot strike (RFS) (62,96). The prevalence of RFS has been associated with a rapid and high-impact peak in the ground reaction force, greater peak tibial acceleration and greater ankle stiffness (85,117–122), and have been associated with a greater injury risk (18,85). Therefore, alternatives to RFS should be explored, such as retraining programs with progressive transitions to FFS.

The effectiveness of acute changes in running retraining programs based on transitions to FFS has previously been examined in laboratory protocols (45,46,119,120,122,255,260). Huang et al. (122) reported a reduction in impact loading by combining FFS and increase cadence. Moreover, Baggaley et al. (119) compared three components of real-time visual feedback during a single session which included: targeting a FFS using the footstrike angle (FSA), decreasing step length by 7.5% and decreasing vertical loading rate by 15%. They found the FFS component had the greatest impact on attenuation strategy compared to the other visual feedback components. This is further supported by Napier et al., (255) who showed a decrease of step length and increase of cadence were associated with a reduction of vertical loading rates and breaking forces after an 8 session laboratory based visual biofeedback training program. In addition, several acute programs have determined that an increase of cadence between 10-15% is associated with a decrease of impact forces, in combination with a transition to FFS, and a decrease in the step length and duration (45,46,260). Therefore, changes in running patterns associated with FFS and increase of cadence, have both been shown to reduce impact attenuation after running retraining programs, which may reduce the risk of injury (18,85,133).

Despite the promising effects of acute laboratory based running retraining programs, the use of sophisticated instruments, e.g., force plates to provide real-time biofeedback, do not have good clinical utility due to availability and cost. Less sophisticated approaches which consider clinically applicable retraining programs, such as increasing the natural cadence using a metronome and transition to FFS, have been shown to be effective in terms of reducing impact forces (121). Another non-laboratory and ecological alternative which encourages an FFS pattern is the transition to barefoot running (181,217). In addition, barefoot running reduces ground-reaction force and loading rates and has been hypothesised to reduce the risk of injury (102,181,216). Tam et al. (188), explored an 8 week barefoot running program, and found a subgroup of responders with a similar pattern. These responders reduced the initial loading rate which could be explained by changes in the FSA and a reduction in the RFS prevalence. In contrast, a similar study showed no significant change in ankle angle, cadence or stride length (318). Therefore, there is still contradictory evidence on how barefoot running programs affect biomechanical outcomes, and little is known about increasing cadence in non-laboratory conditions and progressively over a long period of time.

Despite the number of studies that have considered running retraining programs, few have observed the effect on foot kinematics and spatiotemporal parameters within more ecologically valid, non-laboratory based environments using non-sophisticated clinically feasible programs. Since the RFS prevalence reduction and the cadence increase have been associated with a reduction in the risk of injury (18,85,133), the purpose of this study was to compare the effects of two non-laboratory based 10-week running retraining programs on foot kinematics and spatiotemporal parameters in habitually shod recreational runners. The two retraining programs were: a 10-week barefoot running program, and a 10-week increased cadence running program. Both training scenarios were performed at comfortable speeds. The hypothesis was that both strategies of running retraining would reduce the RFS prevalence and FSA, and increase the cadence when compared to a control group.

Methods and materials

Participants

The subjects came from three different recreational running clubs in Andalusia (Spain), and the assessment protocol was performed in season. Inclusion criteria were: all the subjects were healthy, had participated regularly in aerobic training at least three times per week during the last 2 years, had no history of injury in the previous six months that would limit training. As regards the exclusion criteria, subjects with cardiorespiratory pathologies that affect cardiovascular performance, such as asthma, allergies, diabetes or other cardiac pathologies, were not included. This study conformed to the Declaration of Helsinki (2013) and was approved by the Ethics Committee at the University of Granada (No. 788/CEIH/2019). Each participant was informed about the study and signed an consent form. They were then randomly assigned to one of three groups; a barefoot retraining group (BAR), a cadence retraining group (CAD) and a control group (CON). A recruitment flowchart of the participants is shown in **Figure 46**. Those participants who discontinued the intervention were due to injuries unrelated to the intervention or personal reasons.

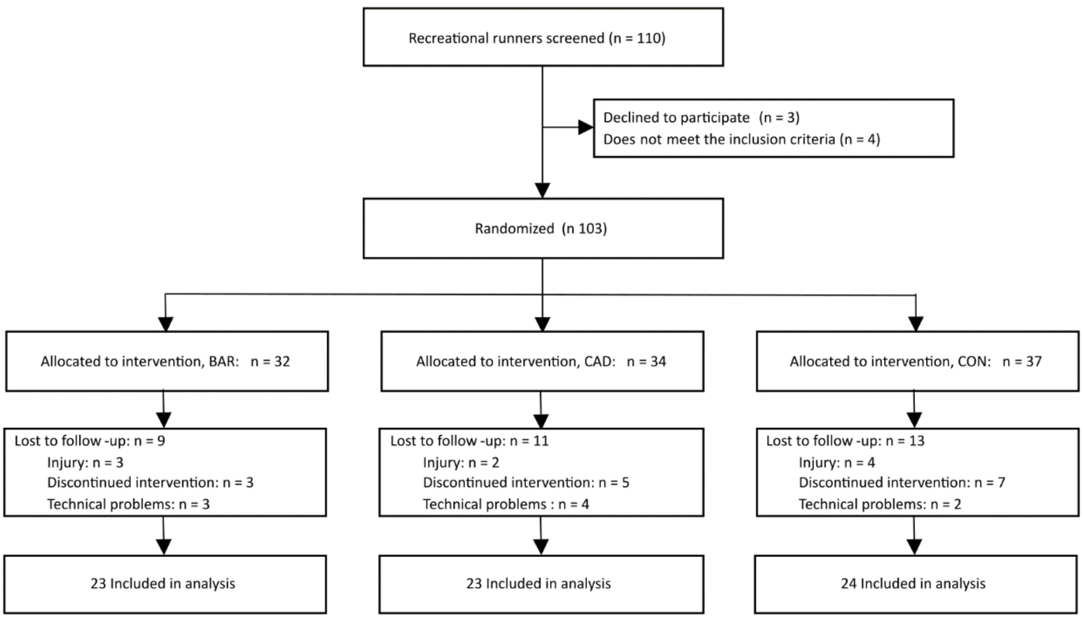

Figure 46. Flowchart of participant recruitment. BAR, Barefoot group; CAD, Cadence group; CON, Control group.

A priori sample size calculation was performed using the G*Power software for ANOVA: repeated measures, with a between groups analysis. The following parameters were selected: moderate effect size f = 0.252, α level of 0.05, a power level of 0.95, Noncentrality parameter λ=16.500, critical F=3.142. The sample size required was determined to be at least 66 participants to assess the three groups at two assessment time points.

Retraining program

The BAR and CAD groups performed three retraining sessions per week, the first 4 weeks during the warm-up and the last 6 weeks were individual retraining sessions (**Table 13**). In addition, they received a weekly training diary, to check that there was at least an 85% adherence and daily retraining intensity using a 0-10 Borg scale score (278). The BAR group performed periods of barefoot retraining following a previously published methodology (231). This consisted of the progressive inclusion of barefoot running on a soft, flat, grass or non-slip surface (i.e., a football pitch), at comfortable speed, medium speed and with progressive runs building to high speed. Increases in running speed have been shown to be effective in reducing the prevalence of RFS (62,231). The CAD group performed a retraining program based on an increase of 10% of their natural cadence at comfortable speed determined at baseline following the protocol suggested by previous studies (45,46,260), and a digital metronome was used to provide auditory feedback (121). The CAD group was asked to strike their feet to the beat of the metronome and, to control the comfortable speed, the retraining sessions were performed either on a treadmill or on a 400-meter running track (controlling the pace by GPS or lap time) both within the same sporting facilities. The choice depended on the runners' abilities, those who had problems following the comfortable speed and the increase in cadence using the metronome carried out the intervention on the treadmill. The runners' coaches and the principal researcher conducted the retraining programs in person, to ensure runners did not experiment with other methods. The principal researcher provided the coaches and runners with the week's retraining task both in writing and verbally on the first training day of the week. Both retraining groups performed progressive, and similar volume and intensity programs. Finally, the CON group did not perform any retraining, and the runners continued with their usual training load. All groups continued with their training loads and habits outside of the retraining sessions, the BAR group wore their running shoes, and the CAD group did not use a metronome, during competitions, high intensity runs on the track or long distance runs in the outdoors. Apart from the instructions described above, none of the retraining groups received any other technical instruction and participants were advised to decrease the intensity of training or even abandon it when pain or injury occurred.

Table 13. Weekly retraining of the experimental groups (repeated 3 times a week)

Weeks	**Barefoot retraining group**	**Cadence retraining group**	**Total weekly time (minutes)**
1	15’ CS	15’ CS	**45**
2	15’ CS	15’ CS	**45**
3	20’ CS	20’ CS	**60**
4	20’ CS + 5 x 80m progressive sprints	20’ CS	**60**
5	25’ CS	25’ CS	**75**
6	25’ CS + 5 x 80m progressive sprints	25’ CS	**75**
7	30’ CS	30’ CS	**90**
8	10’ CS + 10’ MS + 10’ CS	30’ CS	**90**
9	35’ CS + 5 x 80m progressive sprints	35’ CS	**105**
10	10’ CS + 10’ MS +10’ CS +5’ MS +5’ CS	40’ CS	**120**

Note: Comfortable speed (CS); Medium speed (MS)

Materials and testing

Body height and weight were measured to the nearest 0.1 kg and 0.1 cm respectively (SECA Instruments, Germany), and body mass index (kg/m²) was calculated. Additionally, body composition was measured using bioimpedance testing (Inbody 230, Inbody, Seoul, Korea). Two methods were used to record foot kinematics. Firstly, three-dimensional FSA was evaluated using a Simi Motion Capture System composed of eight high-resolution cameras operating at 100 Hz and the Simi Motion software v.9.2.2. (Simi Reality Motion Systems GmbH, Germany). The FSA was examined over a 15 s period (with more than 40 steps), using reflective markers on the running shoes, and computed as the sagittal plane angle of the foot segment, with reference to the lab co-ordinate system at initial contact (282) using Visual3D (C-Motion, Rockville, MD). The marker data were filtered with a cut-off frequency of 8 Hz via a fourth-order Butterworth low-pass filter (120). Initial contact was defined using the technique described by Handsaker et al. (288), which was cross checked against the video recordings. Angles greater than 8.0° were represented as RFS, angles from 8.0° to -1.6° were midfoot strikes and angles less than -1.6° as FFS (282). Secondly, the foot strike pattern was determined using two cameras within the Simi Motion Capture System, which were placed 4 meters perpendicular to the centre of the treadmill using the methods described by Latorre-Román et al. (319). The classification of RFS or non-RFS using these techniques has been shown to have a greater accuracy in determining a RFS (interrater accordance: 0.981), than in deciding between RFS, midfoot strike and FFS (0.893) (115).

Spatiotemporal parameters were recorded using a floor-based photocell system (Optogait; Microgate, Bolzano, Italy), mounted on a professional treadmill (Woodway Pro XL, Waukesha, WI, USA) at a sampling frequency of 1000 Hz, over a 120 s period (with more than 330 steps). Optogait has been previously validated for the assessment of spatiotemporal parameters during running, reporting small systematic biases and random errors and very high ICCs and Pearson coefficients (> 0.9) (202). The parameters obtained were; contact time (CT), and its three subparts, landing time (from the footstrike until the whole foot is in contact with the ground), midstance time (from when the whole foot is in contact until the heel is off the ground), propulsive time (from the moment the heel is off the ground until the foot is completely off the ground). In addition, flight time (FT), step length (SL) and cadence were recorded, which were previously defined by García-Pinillos et al. (70).

Test Protocol

Participants did not perform any heavy physical exertion for 72 hours prior to data collection. They were asked to run consistently on a professional treadmill at their self-selected comfortable training speed and self-selected high speed, defined by a self-declared recent best 5 km pace in the current season. As the purpose was to evaluate the effect of progressive periods of running retraining (e.g., barefoot running) on habitually shod runners, all participants performed the running protocol by wearing their own running shoes in the pre- and post-test (285). Before the running test, they performed an

8 minute warm-up on the treadmill at their self-selected comfortable training speed (70,119). Once the comfortable speed was selected and the warm-up completed, the data collection was carried out with a total period of 120 s. The indications for a comfortable speed were: “Run comfortably at a speed that allows you to speak and breathe easily”. Participants' test speeds were recorded, and the same protocol was repeated at the same speeds after the 10-week running retraining programs. In order to control the potential effect of fatigue during the running test, the intensity was measured using the 0–10 Borg scale (278).

Statistical Analysis

Data were analysed using SPSS, v.25.0 for Windows (SPSS Inc, Chicago, USA) and the significance level was set at $p<0.05$. Tests of normal distribution and homogeneity were conducted on all data before analysis using the Kolmogorov-Smirnov and Levene’s tests respectively, and all data were found to be suitable for parametric testing. Descriptive data were reported in terms of means and standard deviations (SD). A 3x2 analysis of variance (ANOVA) with repeated measures was conducted to examine the effects of time (pre-test and post-test) and groups (BAR, CAD and CON) on each variable. Paired t-tests were used as post-hoc tests when a significant interaction between groups and time was detected. Additionally, effect sizes for group differences were expressed as Cohen’s *d* (291); effect sizes are reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) (291). Regarding the RFS prevalence, a chi-squared (χ^2) test was used to compare the differences between groups, in addition, McNemar´s tests were used to analyse the within-group differences.

Results

Regarding the retraining sessions, the average attendance for the BAR program was 85% with an average score of 3.5 out of 10 on the Borg scale, with the CAD having an average attendance of 86% with an average score of 3.6 out of 10 on the Borg scale. In each acquisition period, no participants indicated a score >6 out of 10 in the Borg scale during the running protocol. At baseline, no significant differences were observed for any of the demographic and training characteristics between the three groups (**Table 14**).

Table 14. Demographic and training characteristics, mean (SD)

	BAR (n = 23, 39.1% females)	CAD (n = 23, 47.8% females)	CON (n = 24, 29.1% females)	P-value
Age (year old)	31.4 (7.37)	29.39 (7.41)	29.21 (7.07)	0.543
Height (cm)	175.3 (10.39)	173.13 (7.23)	173.08 (6.72)	0.593
Body mass (kg)	73.0 (12.21)	69.77 (11.27)	70.22 (11.47)	0.598
Body mass index (kg/m2)	23.7 (2.95)	23.16 (2.53)	23.34 (2.84)	0.795
Fat mass (%)	21.77 (9.44)	20.09 (6.41)	17.36 (5.07)	0.111
Muscle mass (%)	44.96 (4.63)	44.78 (4.14)	46.75 (3.39)	0.192
Comfortable speed (km/h)	9.87 (1.11)	10.15 (1.04)	10.45 (0.86)	0.150
High speed (km/h)	14.03 (2.02)	14.24 (1.93)	15.13 (1.35)	0.095
Training experience (years)	3.43 (1.33)	3.43 (1.65)	3.00 (1.20)	0.457
Running sessions per week	3.76 (1.00)	3.91 (1.12)	3.50 (0.98)	0.625
Training volume per week (km)	26.95 (14.20)	21.87 (11.67)	26.42 (9.34)	0.287
Competitions per year	10.57 (7.87)	8.04 (6.59)	7.25 (4.32)	0.202

Note: Standard deviation (SD); Barefoot group (BAR); Cadence group (CAD); Control group (CON)

Foot kinematics

A significant Time x Group interaction effect was seen for the foot kinematics, **Figure 47**. Further post hoc paired t-tests showed a decrease in FSA after retraining in the BAR group by 5.81° ($p < 0.001$; Cohen's d = 0.749) and 6.54° ($p < 0.001$; Cohen's d = 0.753) at comfortable and high speed, respectively. Similarly, the FSA decreased in the CAD group by 4.84° ($p = 0.002$; Cohen's d = 0.638) and 4.71° ($p = 0.001$; Cohen's d = 0.623) at comfortable and high speeds, respectively. In contrast, the FSA increased in the CON group by 2.70° ($p = 0.047$; Cohen's d = 0.340) at high speed, and no significant changes were found at comfortable speed, after retraining. A significant reduction in RFS prevalence was also seen in the BAR group, for both the left and right feet ($p = 0.006$ and $p = 0.011$), after retraining at comfortable speed only. No significant differences were found for RFS in the CAD and CON group at both speeds after retraining.

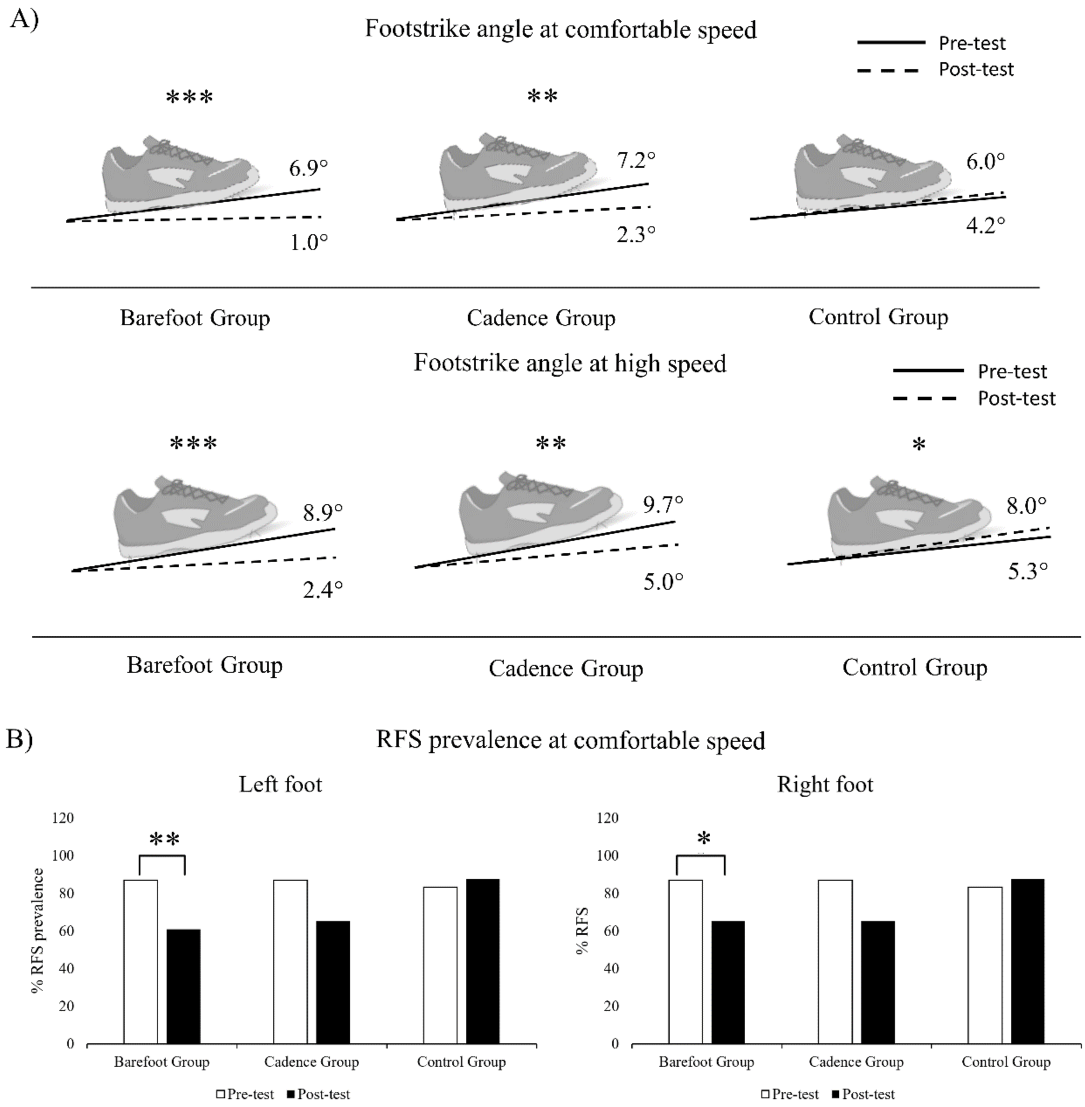

*Figure 47. (A) The footstrike angle (FSA) at comfortable and high speed for pre- test (solid lines) and post- test (dashed line) for each group. (B) rearfoot strike (RFS) prevalence in percentage of runners using a RFS at comfortable speed, by the foot strike pattern (left and right foot) for pre- test and post- test for each group. *denotes p < 0.05; **denotes p < 0.01; ***denotes p < 0.001.*

Spatiotemporal parameters

A significant Time x Group interaction effect was seen for spatiotemporal parameters, *Figure **48***. Further post hoc paired t-tests showed that at the comfortable speed; cadence increased for the CAD group (p = 0.015; Cohen's d = 0. 344) and decreased for the CON group (p = 0.031; Cohen's d = 0. 326); and landing time decreased for the BAR and CAD groups (p = 0.001; Cohen's d = 0.591 and p = 0.008; Cohen's d =

0.472), respectively after retraining. At high speed, further post hoc paired t-tests showed that; SL decreased for the BAR group ($p = 0.030$; Cohen's d = 0.105) and increased for the CON group ($p = 0.001$; Cohen's d = 0.251); and cadence increased for the BAR group ($p = 0.031$; Cohen's d = 0.412) and decreased for the CON group ($p = 0.001$; Cohen's d = 0.534); and landing time decreased for the BAR group ($p = 0.004$; Cohen's d = 0.304) after retraining. No significant differences were found for any other spatiotemporal parameters at both speeds after retraining.

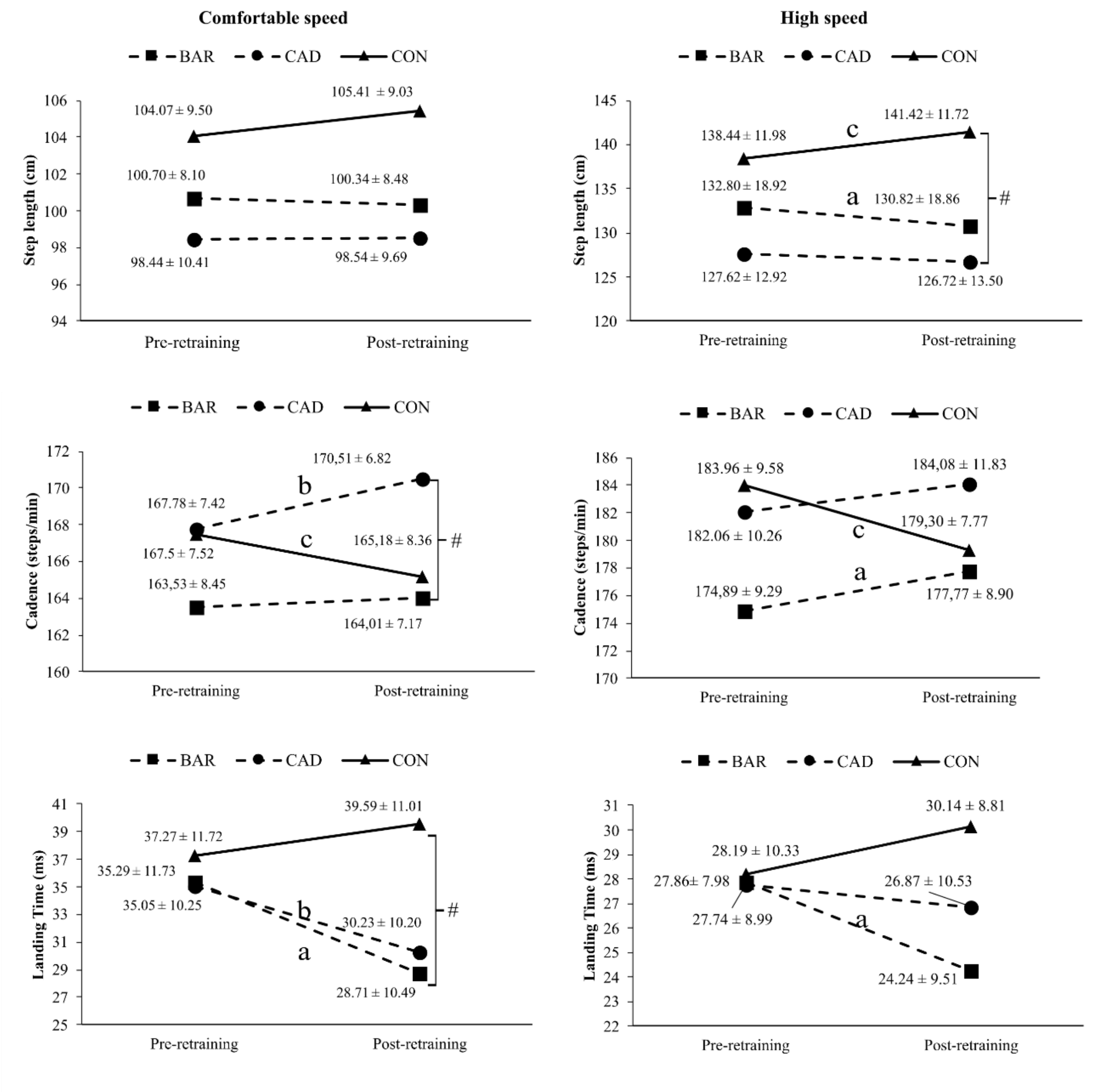

Figure 48. Effect of 10- week retraining programs on step length, cadence, and landing time at comfortable speed (left column) and high speed (right column). Barefoot group (BAR); Cadence group (CAD); Control group (CON); afor BAR, bfor CAD, and cfor CON indicate significant difference between pre- retraining and post- retraining ($p < 0.05$); #indicates an interaction effect between groups ($p < 0.05$)

Discussion

The purpose of this study was to compare the biomechanical effects of two different 10-week non-laboratory based running retraining programs on foot kinematics and spatiotemporal parameters at comfortable and high speeds in recreational runners. To our knowledge, this is the first study to explore the effect of these retraining protocols on foot kinematics and spatiotemporal parameters in recreational endurance runners. The main findings of this study were: 1) FSA was significantly reduced for both the BAR and CAD groups with a moderate effect size, 2) the BAR group decreased RFS prevalence at comfortable speed with a moderate effect size, 3) the cadence was significantly increased for the CAD group at comfortable speed and for BAR at high speed after retraining with small effect sizes, and 4) the CON group decreased cadence at both speeds and increased SL at comfortable speed after the two time points with small effect sizes. Both retraining programs, short-periods of barefoot running and increasing the cadence by 10%, produced significant kinematic changes in FSA, RFS prevalence and spatiotemporal parameters with small to moderate effect sizes. Moreover, no adverse events relating to the exercise program were reported.

Foot kinematics

Compared to the pre-test, the FSA was reduced significantly after BAR and CAD programs at comfortable and high speeds. The whole BAR retraining group reduced the FSA, showing a group mean of 1.0° and 2.4° at comfortable and high speeds after retraining, respectively. Altman et al., (282) defined a midfoot strike with a FSA between 8° and -1.6° based on the strike index using plantar pressure regions. Thus, the BAR group would be considered a midfoot strike after 10 weeks of barefoot retraining. Conversely, an 8 week retraining study based on the combination of barefoot walking and running did not change overall group kinematics (188). Unlike this study, which carried out only 6 out of 24 continuous barefoot running sessions, we planned all sessions with continuous barefoot running at a comfortable speed, with the addition of progressive runs building to high speed and medium speed barefoot running in some retraining sessions. This suggests that the load and intensity of these programs is a determining factor for producing the switch from RFS to midfoot strike or even to FFS. Similarly, the CAD group reduced the FSA, showing a group mean of 2.3° and 5.0° after the retraining program at comfortable and high speeds. The transitions from RFS to non-RFS during laboratory retraining programs have previously demonstrated a reduction of the ankle joint stiffness, impact forces and lower limb load (119–122), associated with a lower injury risk (18,85).

Using a visual 2D video-based determination of RFS (heel strike) and non-RFS (non-heel strike), only the BAR group reduced the RFS prevalence at a comfortable speed after the retraining program. However, a similar study which explored barefoot and cadence retraining programs in adolescents did not find any significant changes (320). They suggested that the rapid growth (i.e., body height and weight) and the deterioration of biomechanics and coordination in adolescents as potential influential factors. Nevertheless, this is supported by other barefoot retraining programs which have been reported to result in effectively reducing RFS prevalence in runners measured by visual 2D video-based analysis in long-distance regional or national athletics championship runners (217). They found a decrease from a RFS prevalence of 80% at baseline to 43% after a 10-week barefoot retraining program. Similarly, we found a decrease for the BAR group from a RFS prevalence of 87% at baseline to 63% at post-test within recreational runners. This, highlighting the importance of sample characteristics on outcome variation in similar barefoot retraining programs, and the importance of intrinsic and extrinsic factors within and between individuals. Since using 2D video-based visual determination can only discriminate between RFS and non-RFS, only large changes can be determined using this method. Therefore, only significant changes were found for BAR by 2D visual determination, whereas using a 3D method, a significant reduction in the FSA was detected for both groups.

The RFS prevalence in road races with recreational runners has been widely studied (62,96,103), however, few studies have tested the effects of retraining programs at high speeds (217) Our results demonstrated a reduction in FSA and RFS prevalence following BAR and CAD retraining programs at high-speed. Which may be related to less contact time and greater flight time (62), proposed as one of the models associated with elastic energy and stiffness of the leg muscles to increase running economy (66,84).

Spatiotemporal parameters

The running retraining programs also induced changes in the SL, the cadence and the landing time. A recent comparison of retraining based on increasing cadence versus a transition to FFS by Futrell et al. (121) showed that cadence retraining increased the cadence by 7.2%, decreasing the vertical average load rate by 16% after retraining, however, the transition to FFS retraining increased the cadence by 6.1% after retraining, with a greater reduction of impact load (vertical average load rate) which decreased by 49.7% and vertical instantaneous load rate which decreased by 41.7%. Thus, Futrell et al suggested that a non-RFS is a more crucial key factor for impact load reduction than cadence. In our current study, the CAD group increased cadence by 2% at comfortable speed, from 167 steps/min to 171 steps/min, after the retraining and the BAR group by 1.7%, from 175 steps/min to 178 steps/min after the retraining at high speed after the retraining program. These findings are not considered as meaningful changes by the authors for cadence, as the target was a 10% increase in cadence for the CAD group, and at least a 6-7% increase has been shown to produce a significant reduction in impact loads (121). However, we suggest that a combination of reduction of FSA and decreasing of RFS prevalence could lead to a reduction of impact loads (121), although, these results need to be evaluated and discussed in real-world applications. The BAR group showed significant changes decreasing landing time after the 10 weeks at both speeds. This change could be related to the transition from RFS to non-RFS where the time and angle range of movement from footstrike to flat foot on the ground is reduced due to an angle at footstrike being close to 0° (217). In contrast to the BAR and CAD groups, the CON group showed minor changes with a 2% decrease in cadence at both speeds, and an increase in SL at high speed, after the two time points. The use of traditional running footwear has been associated with a high RFS prevalence and SL, and a low cadence (18,62,85,96). As for the CON group, this could be due to a natural tendency of endurance runners, who habitually wear shoes, which could lead to an increase in FSA, and may be related to a high RFS prevalence, decreased cadence and increased SL.

Limitations

Several limitations need to be acknowledged in the current study. Although this study considers the effect of two 10-week running retraining programs in healthy recreational runners, the extrapolation of these results to injured, elite, juvenile or long-distance competitive runners should be done with caution. Due to the small sample size of the current study, it was not possible to analyse effects by gender. The 10-week effects of the retraining programs were tested, so the longer-term effects of these programs are unknown. In addition, the runners presented relatively high cadences at baseline (166 steps/min and 180 steps/min at each speed), making the 10% increase set by the study difficult to achieve (183 steps/min and 198 steps/min).

Perspectives

Despite the promising effects of acute laboratory based running retraining programs used to try to reduce the incidence of injury (45,119,120,122,255,260,321), to our knowledge, little is known about the effect of ecologically valid, non-laboratory based environments using non-sophisticated clinically feasible programs on foot kinematics and spatiotemporal parameters in recreational runners.

Changes in running patterns associated with FFS and increases to the cadence, have both been shown to reduce impact attenuation after running retraining programs (45,46,119–122,260). Running barefoot encourages a midfoot strike pattern, and could reduce ground-reaction force and loading rates in recreational runners (181,217), thus, it has been hypothesized to be a valid non-laboratory and ecological alternative to reduce the risk of injury (102,181,216). Therefore, our findings represent a contribution to our understanding to the knowledge on running retraining effects in foot kinematics and spatiotemporal parameters by assessing these two feasible tools. Both methods are useful for clinical applications for trainers, physiotherapists, or other clinicians working with recreational runners who want to reduce footstrike angle and rearfoot strike prevalence for practical purposes.

Conclusions

The BAR and CAD retraining programs showed moderate reductions in foot strike angle and prevalence of rearfoot strike. Cadence did not effectively increase for the BAR and CAD groups, showing minor changes together with a reduction in step length after the two retraining programs. The two proposed running retraining programs appear to reduce footstrike angle and rearfoot strike prevalence, however, they were not as effective in increasing cadence after 10 weeks of progressive retraining sessions.

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Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

AM-M, PAL-R and VMS-H defined the experimental design and conceptualised the approach. AM-M, EM-P and GD-G collected the data. PAL-R and JR carried out the statistical analysis. AM-M wrote the paper. All authors reviewed the manuscript for scientific content. All authors have read and agreed to the published version of the manuscript.

Ethical approval

This study conformed to the Declaration of Helsinki (2013) and was approved by the Ethics Committee at the University of Granada (No. 788/CEIH/2019).

Informed consent

Informed consent was obtained from all individual participants included in the study

STUDY 3. INCREASING CADENCE AND RUNNING BAREFOOT CHANGES LOWER LIMB AND TRUNK SAGITTAL KINEMATICS

STUDY 3

Increasing cadence and running barefoot changes lower limb and trunk sagittal kinematics

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Abstract

Previous studies have demonstrated, separately, the effects of barefoot running and increased cadence with similar results, such as altering spatiotemporal parameters and lower limb kinematics. However, there is uncertainty in the evaluation of these programs in the same study population with similar training loads. The purpose was to compare the effects of two non-laboratory based running retraining programs on lower limbs and trunk kinematics in recreational runners at comfortable speed and high speed. Sixty-eight recreational runners (30 ± 7.3 years old, 38% females) were randomly assigned to a barefoot group (BAR), a cadence group (CAD) or a control group (CON). BAR include short intervals of barefoot running while CAD increased baseline cadence at comfortable speed by 10% Both retraining programs included three sessions per week over 10 weeks. 3D sagittal kinematics of the ankle, knee, hip, pelvis and trunk were measured before and after the retraining program, at comfortable speed and high speed. A 3 × 2 ANOVA revealed that the BAR and CAD groups increased knee flexion at footstrike, decreased maximal extension at initial swing phase, increased hip flexion, and increased anterior pelvic tilt, at comfortable and high speed after retraining. In addition, BAR showed increased ankle plantar flexion in the footstrike and increased anterior trunk tilt. Significant moderate to large effect size changes were found for both running retraining programs, demonstrating similar motor familiarisation using clinically unsophisticated tools that could reduce the mechanical risks of injury associated with excessive knee stress. Changes found at comfortable speed (target speed of intervention) were also found at high speed, which could lead to changes in running performance.

Key words: barefoot, metronome, step rate, unshod, running retraining.

Introduction

Endurance running is an activity that has become widespread among the recreational population with the aim of improving health and personal performance (8,9). However, the annual incidence of running-related injuries can rise to 74% among long-distance runners (16–18). An excessive knee stress and a high vertical and horizontal impact force have been associated to running-related injuries such as knee injuries (131,132), which are most common among recreational long-distance runners (21). Running retraining as a process of learning a new running motor pattern is of interest for enhancing performance, injury prevention and rehabilitation (243). A basic purpose of retraining in runners is to modify a motor pattern associated with a potential risk of running-related injuries caused by overuse, considered as a faulty motor pattern. Recent evidence shows that real-time biofeedback interventions based on impact forces can effectively reduce injury prevalence (119) and elicit kinematics changes such as transition to forefoot strike (119,122), reduction of the step length (119) or anterior trunk tilt (122). However, many real-time biofeedback interventions are restricted to laboratory settings, which limits its practical applicability.

Increasing cadence has been proposed as a method for running retraining that could be integrated in a non-laboratory setting through the use of a mobile metronome application (48,245,248), and has been suggested for impact attenuation and knee stress reduction (254,322–324). Concretely, increasing the cadence by 10% has been associated with an immediate decrease in impact forces in a laboratory setting where participants were instructed to self-administer the cadence in real time (45,46,260). In addition, a two-week retraining program increasing cadence promotes transition to forefoot strike, reduce impact forces, foot strike angle and step length, and generates changes in ankle, knee, hip and lumbopelvic kinematics (254). After 10-12 weeks of retraining out the lab with a 10% increased cadence, participants increased their baseline cadence from 2% to 5.7%, decreased footstrike angle (48,245), impact forces, and peak knee flexion (245).

Barefoot running has also been considered as an non-laboratory retraining alternative which encourages impact attenuation (85,187,188) and has been hypothesised to reduce the risk of injury (85,216,217). An 8-week barefoot running program found a subgroup of responders who reduced impact forces, which could be explained by changes in ankle flexion angle at footstrike (188). Moreover, 10-12 weeks of barefoot running increased prevalence of forefoot strikes (48,217), reduced footstrike angle, reduced step length and increased cadence (48), similar results to those of running retraining with a 10% cadence increase (245,248,254,323). However, an 8-week barefoot running program, showed no significant change in ankle angle, cadence or stride length (318). Thus, while several studies on barefoot running provide strong evidence of reduced impact (187,188), and changes on foot kinematics and spatiotemporal parameters (48,188,217,318), the effects of a long-term retraining program on lower limb kinematics (i.e. ankle, knee, hip and pelvis) have not been well established. To date, only one study has compared increasing cadence versus barefoot running on the effect on biomechanical outcomes (focusing on spatiotemporal parameters and foot kinematics), controlling that runner characteristics, volume and intensity were similar between the two retraining programs (48).

Therefore, the aim of this study was to compare the effects of two non-laboratory based 10-week running retraining programs (barefoot vs. cadence increase) on lower limbs and trunk running kinematics in recreational runners at comfortable and high speed. Based on previous research, it is hypothesised that running barefoot and increasing cadence by 10% would generate similar changes in ankle, knee, and hip kinematics, although the available data are not sufficient to formulate a more precise hypothesis. In addition, there is insufficient information on their effects on pelvic and trunk kinematics, as many studies have focused on their effects on the foot, ankle and knee. This research is of interest to scientists, coaches and runners as it yields new insights into the kinematic changes of different user-friendly and field-based running retraining programs.

Methods and materials

Experimental design

The study consists of a running retraining program including two intervention groups (barefoot running and cadence increase) and a control group. The outcomes corresponded to changes from baseline in the angles of ankle, knee, hip, pelvis and trunk, and angular velocities of ankle, knee and hip. These variables were measured at two different running paces: i) comfortable speed (CS) that was self-selected by the runners in the warm-up, and ii) high speed (HS), selected considering the best 5 km pace in the current season. The participants visited the laboratory twice, at baseline (pretest) and at the end of the running retraining program (postest). Prior to data collection, they did not perform any heavy physical exertion for 72 h.

Participants

A total of 103 runners were initially recruited from local running clubs, and randomly assigned to one of three groups; a barefoot retraining group (BAR), a cadence retraining group (CAD) and a control group (CON). Inclusion criteria were: all the participants were healthy, had regularly participated in running training with a minimum frequency of three sessions per week over the last two years, and had no history of injury in the previous six months that would limit training. In terms of exclusion criteria, participants with cardiorespiratory diseases such as asthma, allergies, diabetes, or other cardiac pathologies were not included. G*Power 3.1 software was used to derive a sample size of 66 based on a two-tailed procedure and a repeated measures ANOVA with a between groups analysis. The following parameters were selected: moderate effect size ($f = 0.252$), α level of 0.05, a power level of 0.95, a non-centrality parameter (λ) of 16.500, and a critical F of 3.142. This study conformed to the Declaration of Helsinki (2013) and was approved by the Ethics Committee at the University of Granada (No. 788/CEIH/2019). Participants were informed about the study and signed an consent form. Those participants who discontinued the study were due to injuries unrelated to the retraining programs or personal reasons.

Instruments and procedures

Body height and weight were measured to the nearest 0.1 kg and 0.1 cm respectively (SECA Instruments, Germany), and body mass index (kg/m^2) was calculated. An 8-camera motion capture system (model mvBluecougar-XD104C, Matrix Vision GmbH, Germany) operating at 100 Hz with a resolution of 2048 x 1088 pixels and the Simi Motion software v.9.2.2. (Simi Reality Motion Systems GmbH, Germany) were used to collect kinematic data. A total of 28 markers were placed on the participants according to the International Society of Biomechanics (ISB) standard (283,284). Following the placement of all anatomical markers, the subject was asked to stand on the treadmill for a static trial which was performed to define anatomic coordinate systems for the foot, shank, thigh, pelvis and trunk (283,284). Retroreflective markers were placed bilaterally on the acromioclavicular joint, posterior superior iliac spine, anterior superior iliac spine, femur greater trochanter, thigh, femur lateral epicondyle, femur medial epicondyle, shank, fibula apex of lateral malleolus, tibia apex of medial malleolus, second and third metatarsal heads and posterior surface of the calcaneus. Two additional markers were placed on the spinous process of the 7th cervical and 8th thoracic vertebra.

Before the running test, they were asked to run consistently on a professional treadmill (Woodway Pro XL, Waukesha, WI, USA) during an 8 minute warm-up at their self-selected comfortable speed (CS) and wearing their own running shoes (48). Once the CS was selected and the warm-up completed, participants were instructed to run consistently for 120 s and the data collection was carried out during the last 15 s. The indications for the CS condition were: “Run comfortably and non-stop at a speed that allows you to speak and breathe easily”. Once the CS was recorded, they were asked to run consistently without stopping at high speed (HS) for 120 s and the data collection was carried out during the last 15 s. HS was defined by participants’ best 5 km pace in the current season (48). To control for the potential effect of fatigue during the running test, intensity was measured using Borg’s 0–10 scale (278).

Kinematics data processing

The Visual 3D software (v6; C-Motion, Rockville, MD) was used to compute the 3D running kinematic variables. The raw data were filtered with a cut-off frequency of 8 Hz via a fourth-order Butterworth low-pass filter (120). Footstrike was defined using the technique described by Handsaker et al. (288), which was cross checked against the video recordings. An eight-segment model of the lower limb and trunk was constructed using Visual 3D to calculate the maximum, minimum, footstrike and take-off angles for the ankle, knee, hip joints; and the pelvis and trunk segments, **Figure 49**. In addition to the angular velocities of the ankle, knee and hip.

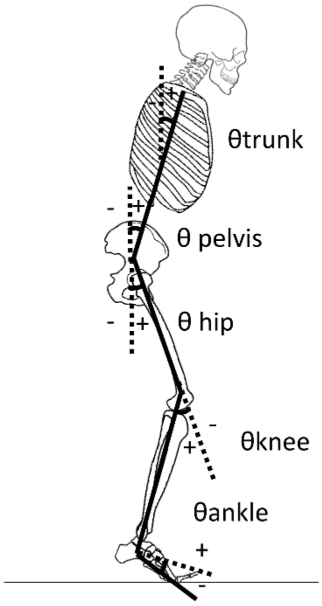

Figure 49. Calculated joint and segmental angles.

Retraining program

The retraining programs were led by blinded runner and coaches; and supervised by the principal researcher with regular random visits to the track every week, to ensure runners did not experiment with other methods. The BAR and CAD groups performed three retraining sessions per week with similar workload between programs, **Figure 50**, adapted from a previously published methodology (231)**,** with previously published outcomes (48)**.** Both retraining programs constituted part of the participants' running volume and kept their weekly volume unchanged. The BAR group performed a progression of barefoot runs on a soft, flat, non-slip grass surface (i.e., a football pitch). During the 10-week intervention the BAR group performed on weeks 4, 6 and 9, 5 sets x 80m barefoot progressive sprints and combined 10 min barefoot running at CS with 10 min at HS up to the total session time on weeks 8 and 10 (48). The CAD group was asked to strike their feet to the beat of a metronome increased by 10% of their baseline cadence (at pre-test) at a CS. This speed was controlled on a treadmill, or using a GPS, or by lap time running on a 400-metre track, depending on the runners' preferences or abilities to maintain their CS. Both groups received a weekly training diary, setting a minimum of 85% compliance, and monitoring the intensity of the sessions using the Borg scale from 0 to 10 (278). Finally, the CON group continued with their usual training load, not conducting retraining sessions. All participants were advised to decrease the intensity or even abandon the retraining program if pain or injury occurred.

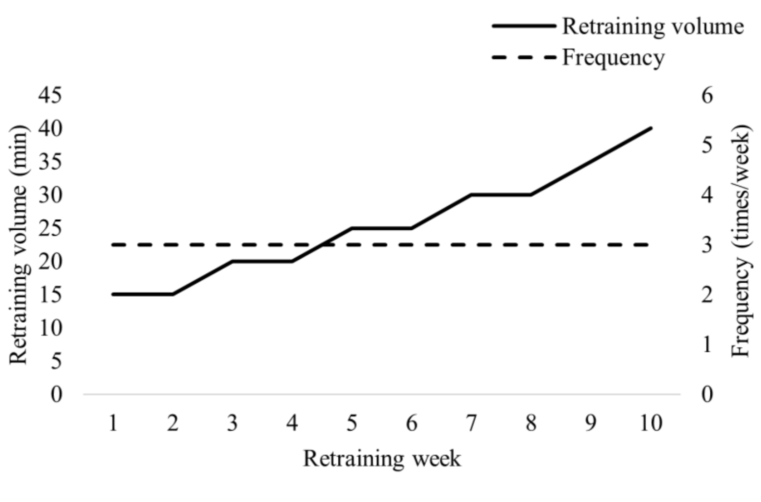

Figure 50. Workloads of running retraining programs at comfortable speed.

Statistical Analysis

The distribution and homogeneity of all data were tested before analysis using the Kolmogorov-Smirnov and Levene's tests respectively, and all data were found to be suitable for parametric testing. Descriptive data were reported using the mean and standard deviations (SD). A 3 x 2 analysis of variance (ANOVA) with repeated measures was conducted to examine the effects of time (pre-test and post-test) and groups (BAR, CAD and CON) for each variable. Paired t-tests were used as post-hoc tests when a significant interaction between groups and time was detected. The significance level was set at $p < 0.05$. Additionally, effect sizes for group differences were expressed using Cohen's *d* (291) and reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) (291). All data were analysed using SPSS, v.25.0 for Windows (SPSS Inc, Chicago, USA). To verify that there were no differences between groups at baseline, a one-way ANOVA was used for continuous variables and a chi-square test ($\chi 2$) was used for the sex variable (dichotomous).

Results

Out of the 103 recruited participants, 77 completed the retraining program with an average attendance of 85% and less than 3.6 out of 10 on the Borg scale. Finally, 70 participants were included in the analysis due to technical problems with the automatic tracking (mainly due to occlusion or bright spots misidentified as a retroreflective marker). In each acquisition period, no participants indicated a score >6 out of 10 in the Borg scale during the running protocol. There were no differences for any of the demographic and training characteristics between the three groups, except for baseline cadence at high speed (**Table 15**).

Table 15. Demographic, anthropometric and training characteristics of runners expressed as mean (SD)

Variable	BAR (n = 23)	CAD (n = 23)	CON (n = 24)	P value
Gender (percentage)	39.1 % females, 60.9% males	47.8% females, 52.2% males	29.1% females, 70.9% males	0,432
Age (year old)	31.4 (7.4)	29.4 (7.4)	29.2 (7.1)	0.543
Height (cm)	175.3 (10.4)	173.1 (7.2)	173.1 (6.7)	0.593
Body mass (kg)	73.0 (12.2)	69.8 (11.3)	70.2 (11.5)	0.598
Body mass index (kg/m^2)	23.7 (3.0)	23.2 (2.5)	23.3 (2.8)	0.795
Baseline cadence at comfortable speed (steps/min)	163.5 (8.5)	167.8 (7.4)	167.5 (7.5)	0.228
Baseline cadence at high speed (steps/min)	174,9 (9.3)	182.1 (10.3)	183.96 (9.6)	**0.009**
Comfortable speed (km/h)	9.9 (1.1)	10.2 (1.0)	10.5 (0.9)	0.150
High speed (km/h)	14.0 (2.0)	14.2 (1.9)	15.1 (1.4)	0.095
Training experience (years)	3.4 (1.3)	3.4 (1.7)	3.0 (1.2)	0.457
Running’s sessions (n/wk.)	3.8 (1.0)	3.9 (1.1)	3.0 (1.0)	0.625
Workload per week (kms)	27.0 (14.2)	21.9 (11.7)	26.4 (9.3)	0.287
Competitions per year (n)	10.6 (7.9)	8.0 (6.6)	7.3 (4.3)	0.202

A significant Time x Group interaction effect was seen for the joint and segment angles. Further post hoc paired t-tests showed that BAR and CAD groups, **Figure 51**, **Figure 52** and **Table 16**; increased knee flexion and hip flexion at footstrike; increased hip flexion during stance phase, during early flight phase, and during flight phase; and increased maximum pelvic anterior tilt and minimum pelvic anterior tilt (at both speeds); and decreased peak knee extension during early flight phase (at comfortable speed) after retraining. Additionally, the BAR group increased ankle plantarflexion at footstrike, maximum trunk anterior tilt and minimum trunk anterior tilt (at both speeds); and decreased peak ankle dorsiflexion during flight phase (at high speed), after retraining. In contrary, the CON group decreased hip flexion at footstrike (at high speed) and during early flight phase (at both speeds); and decreased maximum pelvic anterior tilt, minimum pelvic anterior tilt and maximum trunk anterior tilt (at comfortable speed), and minimum trunk anterior tilt (at both speeds) after the two time points.

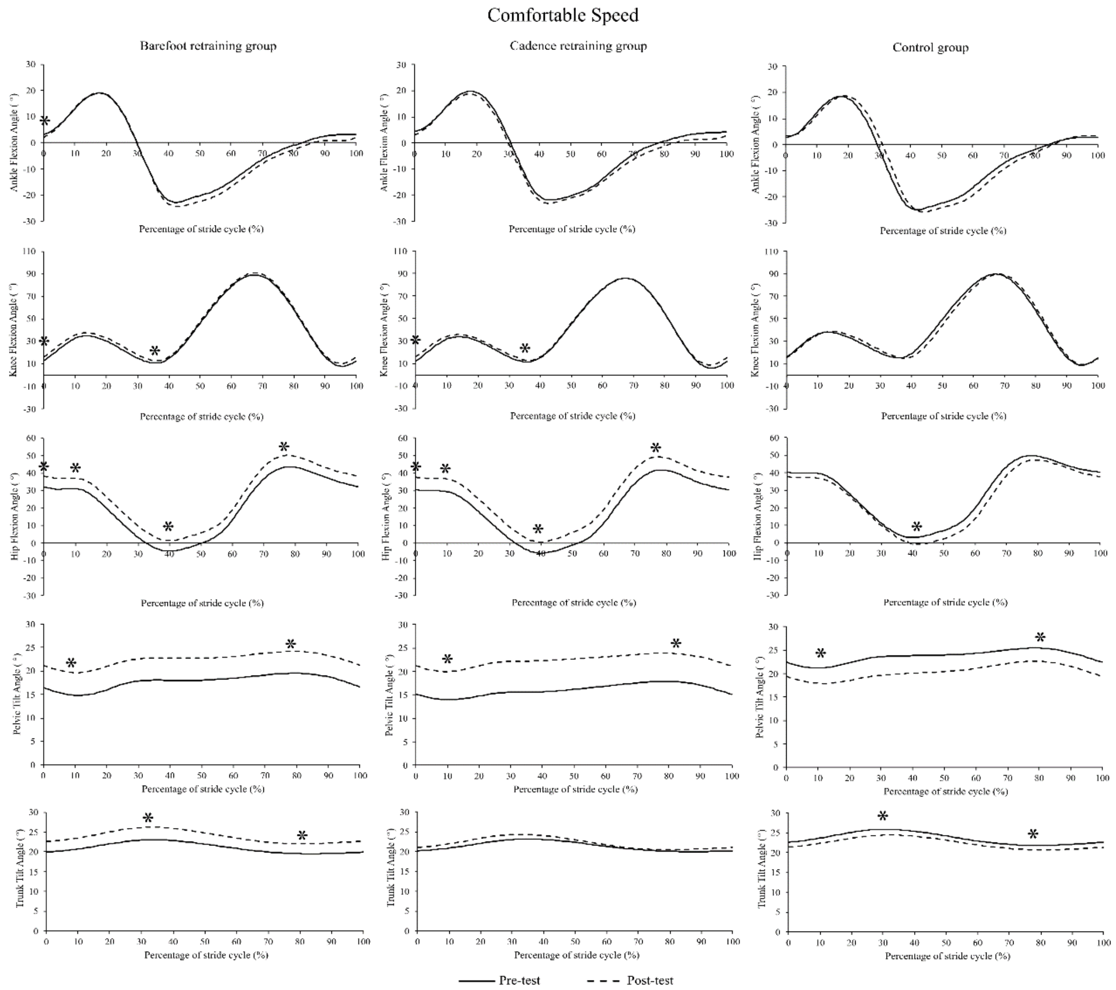

*Figure 51. Changes during the stride cycle for the joint and segmental angles after the 10-week retraining programs at comfortable speed (*denotes significant difference between pre-test and post-test when an interaction effect between Time × Group was seen).*

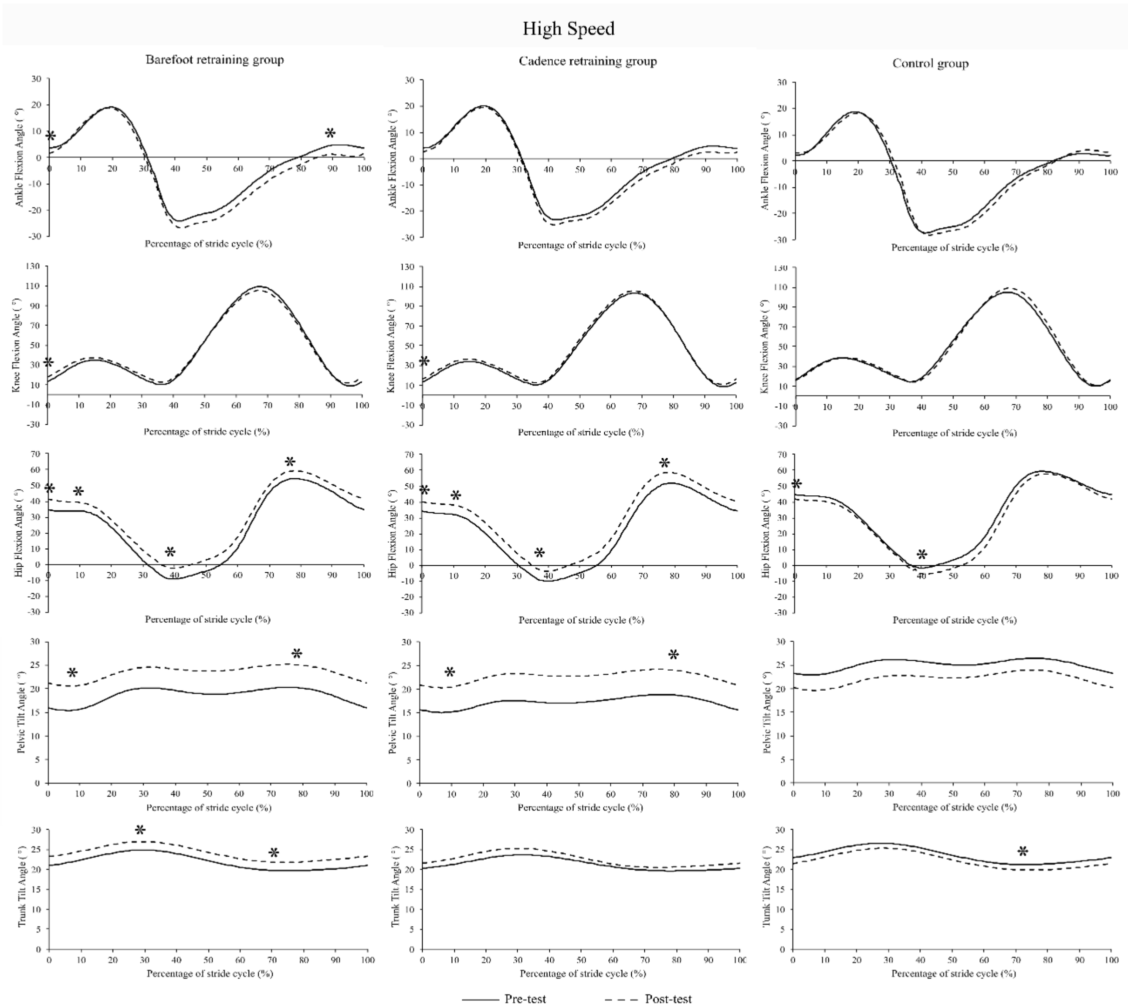

*Figure 52. Changes during the stride cycle for the joint and segmental angles after the 10-week retraining programs at high speed (*denotes significant difference between pre-test and post-test when and interaction effect between Time × Group was seen).*

A significant Time x Group interaction effect was seen for the joint angular velocities. Further post hoc paired t-tests, **Table 16**, showed that; BAR and CAD groups increased peak ankle dorsiflexion velocity during stance phase (at comfortable speed and only for BAR group at high speed); CAD group decreased peak hip extension velocity during stance phase at (at comfortable speed); and finally, CON group decreased peak ankle dorsiflexion velocity during stance phase (at both speeds), and increased peak ankle plantarflexion velocity during stance phase (at high speed), after the two time points.

Table 16.. Post hoc paired t-tests for angles and angular velocities before (pre-test) and after (post-test) the 10-week programs at comfortable and high speed.

Speed	Phase	Variable	Barefoot retraining group		Cadence retraining group		Control group	
			Mean difference	P value (Cohen´s d)	Mean difference	P value (Cohen´s d)	Mean difference	P value (Cohen´s d)
Comfortable speed	Stance Phase	Ankle flexion at footstrike (°)	-2.09 ± 0.91	**0.024 (0.40)**	-1.16 ± 0.87	0.186 (0.26)	0.93 ± 0.85	0.159 (0.28)
		Knee flexion at footstrike (°)	5.10 ± 1.09	**<0.001 (1.01)**	4.70 ± 1.04	**<0.001 (0.91)**	-0.44 ±1.02	0.524 (0.13)
		Hip flexion at footstrike (°)	6.53 ± 1.65	**<0.001 (0.96)**	6.76 ± 1.54	**<0.001 (1.06)**	-2.90±1.54	0.064 (0.46)
		Peak hip flexion (°)	6.28 ± 1.70	**<0.001 (0.88)**	6.21 ± 1.62	**<0.001 (1.00)**	-3.16 ±1.59	0.051 (0.50)
		Peak ankle dorsiflexion velocity	30.68 ± 9.87	**0.003 (0.50)**	20.64 ± 9.87	**0.041 (0.39)**	-21.19 ± 9.43	**0.028 (0.57)**
		Peak hip extension velocity (°/s)	8.90 ± 7.13	0.117 (0.86)	-14.53 ± 6.65	**0.033 (0.30)**	3.79 ± 6.51	0.563 (0.49)
	Flight Phase	Peak knee extension (°)	3.19 ± 0.84	**<0.001 (0.86)**	2.07 ± 0.82	**0.014 (0.60)**	0.16 ± 0.78	0.844 (0.03)
		Peak hip extension (°)	8.01 ± 1.66	**<0.001 (1.27)**	6.63 ± 1.59	**<0.001 (1.08)**	-3.65 ±1.52	**0.019 (0.48)**
		Peak hip flexion (°)	8.25 ± 1.92	**<0.001 (1.11)**	6.92 ± 1.83	**<0.001 (0.92)**	-2.39 ±1.75	0.178 (0.33)
	Full cycle	Maximum pelvic anterior tilt (°)	5.58 ± 1.40	**<0.001 (1.01)**	5.56 ± 1.36	**<0.001 (1.10)**	-3.16 ± 0.12	**0.018 (0.53)**
		Minimum pelvic anterior tilt (°)	5.82 ± 1.40	**<0.001 (1.04)**	6.00 ± 1.36	**<0.001 (1.15)**	-3.58 ± 0.08	**0.008 (0.55)**
		Maximum trunk anterior tilt (°)	2.05 ± 0.56	**0.001 (0.59)**	0.91 ± 0.54	0.094 (0.27)	-1.48 ± -0.42	**0.005 (0.41)**
		Minimum trunk anterior tilt (°)	1.57 ± 0.54	**0.005 (0.39)**	0.38 ± 0.51	0.458 (0.11)	-1.50 ± -0.26	**0.003 (0.50)**
High speed	Stance Phase	Ankle flexion at footstrike (°)	-3.19 ± 0.95	**0.001 (0.58)**	-1.41 ± 0.93	0.134 (0.29)	1.30 ± 0.91	0.140 (0.28)
		Knee flexion at footstrike (°)	4.81 ± 1.08	**<0.001 (0.85)**	3.77 ± 1.03	**0.0001 (0.71)**	-0.64 ± 1.00	0.524 (0.13)
		Hip flexion at footstrike (°)	6.55 ± 1.83	**0.001 (0.85)**	4.73 ± 1.75	**0.009 (0.66)**	-3.43 ± 0.77	**0.049 (0.42)**
		Peak hip flexion (°)	5.71 ± 1.80	**0.002 (0.70)**	4.66 ± 1.71	**0.008 (0.65)**	-3.24 ± 1.66	0.058 (0.40)
		Peak ankle dorsiflexion velocity	52.44 ± 14.24	**< 0.001 (0.78)**	28.28 ± 14.24	**0.051 (0.29)**	-30.22 ± 13.60	**0.030 (0.45)**
		Peak ankle plantarflexion velocity	-27.03 ± 15.60	0.088 (0.64)	-18.11 ± 15.24	0.240 (0.36)	31.75 ± 15.60	**0.046 (0.59)**
	Flight Phase	Peak ankle dorsiflexion (°)	-4.14 ± 1.06	**<0.001 (0.63)**	-1.13 ± 1.04	**0.278 (0.24)**	0.82 ± 1.01	0.421 (0.17)
		Peak hip extension (°)	7.66 ± 1.75	**<0.001 (1.07)**	6.13 ± 1.67	**<0.001 (1.00)**	-3.81 ± 1.63	**0.023 (0.49)**
		Peak hip flexion (°)	8.28 ± 1.87	**<0.001 (0.86)**	6.76 ± 1.78	**<0.001 (0.85)**	-1.23 ± 1.74	0.484 (0.14)
	Full cycle	Maximum pelvic anterior tilt (°)	6.69 ± 1.67	**<0.001 (1.01)**	4.16 ± 1.59	**0.011 (0.76)**	-2.82 ± 1.59	0.081 (0.46)
		Minimum pelvic anterior tilt (°)	6.98 ± 1.79	**<0.001 (0.93)**	4.48 ± 1.71	**0.011 (0.75)**	-2.46 ± 1.67	0.142 (0.32)
		Maximum trunk anterior tilt (°)	2.13 ± 0.66	**0.002 (0.51)**	1.178 ± 0.62	0.064 (0.32)	-1.21 ± 0.61	0.052 (0.30)
		Minimum trunk anterior tilt (°)	1.81 ± 0.58	**0.003 (0.36)**	0.61 ± 0.56	0.277 (0.15)	-1.54 ± 0.19	**0.006 (0.47)**

Post-hoc paired tests were used when a significant interaction effect between Time × Group was seen. Bold denotes p > 0.005. A positive value in the mean difference indicates an increase from the pre-test to the post-test and vice versa.

Discussion

The results of the study confirmed the hypothesis that barefoot running and a 10% cadence increase generated similar changes in ankle, knee, hip and trunk kinematics at comfortable and high speed. To our knowledge, this is the first study to explore the two retraining programs' relative effect on lower limb and trunk running kinematics in a similar cohort of recreational endurance runners. The main findings of this study were: i) the BAR and CAD groups increased knee and hip angle flexion, and pelvic anterior tilt with a moderate or large effect size at both speeds; and ii) the BAR group significantly reduced ankle dorsiflexion and increased trunk anterior tilt with a small or moderate effect size at both speeds. Both retraining programs produced significant kinematic changes on lower limbs and trunk running kinematics with large effect sizes. Moreover, there were no adverse events during the retraining sessions.

Previous findings from immersive programs to barefoot running or with habitual barefoot runners showed an increase in knee flexion at footstrike and at 10% of the stance, and a decrease in peak knee flexion at mid-stance, as well as a decrease in foot angle at footstrike (48,177,187,188), and a decrease in hip flexion at footstrike (213). The knee and ankle appear to be the two joints most sensitive to alterations after barefoot running. Compared to previous transitions to barefoot running, our results are consistent as runners increased knee flexion at footstrike, and decreased ankle angle. However, with the notable difference that the present transition to barefoot running does not attempt to remove the use of footwear, but to combine periods of barefoot running with shod running, evaluating its effect on shod running after 10 weeks. In addition, our results showed an increase in hip flexion, anterior pelvic tilt and anterior trunk tilt during the running cycle. This is a finding not mentioned by several barefoot running programs, mainly because the kinematics of the pelvis and trunk were not studied, focusing on the foot, ankle and knee (187,188,318). Nevertheless, and in similarity with our findings, a greater hip flexion, greater knee flexion and less dorsal ankle flexion at footstrike has been observed in habitually barefoot runners (85), or running with a forefoot strike (254). Therefore, the BAR group, performing a program of barefoot running periods with shod running, presented a similar running performance to habitual barefoot runners when assessed running shod.

The current 10-week program increasing the baseline cadence using a mobile metronome (CAD group) showed an increase in knee flexion at footstrike, and an increase in hip flexion and anterior pelvic tilt throughout the running cycle. Our results are in agreement with those found by Heiderscheit et al. (45) who found an increase in knee flexion at footstrike and, Lenhart et al. (260) who also found an increase in knee flexion at footstrike, in addition to a decrease a decrease in knee flexion and ankle flexion (decrease in dorsiflexion) at mid-phase. None of these studies found kinematic changes for the hip, and the pelvis kinematics was not measured, but Lenhart et al. (260) observed a reduction in the muscle activity of the hip extensors (e.g. gluteus maximus), and our results showed a reduction in the peak velocity of hip extension, which could be related to a lower energy generation during the propulsion phase (77). Comparing our results with a non-laboratory setting using a mobile metronome with a duration of 12 weeks (245), knee flexion at mid-stance was decreased, however, no changes in knee flexion at footstrike neither hip kinematics were found. While their runners had a baseline cadence of 161.3 steps per minute, our runners had a cadence of 167.8 steps per minute. Therefore, we suggest that the baseline cadence of our study sample may have already been too high, which affected the motor pattern, leading to further changes in the hip and knee. In our previous findings from the present experimental protocol (48), concerning spatio-temporal parameters, we observed a significant increase of only 2% in cadence after 10 weeks of intervention. Our findings suggest that although there are some shared kinematic changes between studies, there is no predominant pattern when comparing our findings with those of other studies and further research is needed.

As mentioned above, both 10-week retraining programs, the 10% cadence increase and barefoot running, share several kinematic alterations at the knee, hip and pelvis. These shared kinematic changes have been associated to a reduction in peak knee force by 14%, and hip, knee and ankle joints decreased peak muscle extensor forces (260), and lower mechanical energy absorption for the knee and hip (20). An anterior increase in trunk lean (observed only in the BAR group after 10 weeks of intervention) has been associated with an effective transition to forefoot strike, a decrease in step length (254), and may decrease the lumbopelvic load (41). Therefore, these changes have been suggested strong predictor for reduction in patellofemoral joint loading (45,46,187,188,260), and the prevention of high impact injuries, such as, patellofemoral pain syndrome (325), iliotibial band syndrome (326) and tibial stress fractures (301).

However, caution should be exercised in this regard, as no muscle activations or kinetic parameters were measured in the current study.

In the opposite direction to the two running retraining programs, alterations were found in the CON group. With a more extended hip, posterior pelvic tilt and posterior trunk tilt with a small to moderate effect size. These kinematic changes are those observed with regular use of running shoes, as opposed to barefoot running or increased cadence (18,85), and with the effect of accumulated fatigue (327). It is worth mentioning that the experience of the participants was low. (e.g., CON group; 26.4 ± 9.34 km per week), compared to highly trained long-distance runners (105.3 ± 33.5 km per week) (177). Therefore, we suggest that the changes in the CON group could be due to the daily use of shoes in inexperienced or low-level endurance runners, or an effect of excessive accumulated fatigue during the season. However, we have no information on the footwear worn by participants or physiological parameters of internal loading throughout their training.

It is noteworthy that considering that both running retraining programs were carried out at a comfortable speed, our results showed very similar changes on the kinematics of the lower limbs in the high-speed condition. Corroborating that not only the new motor pattern was acquired at the same speed as the retraining sessions, but also the learning was transferred to higher running speeds for both retraining programs. Two studies tested the effects of similar retraining programs carried out at a comfortable speed on high being their variables the foot kinematics and spatiotemporal parameters (48,217), thus, to our knowledge, this is the first study to test changes in ankle, knee, hip, pelvis and trunk kinematics using a three-dimensional motion capture system for these two retraining programs. We suggest that the effects of both retraining programs should be studied in real competition situations, since, it has been suggested that barefoot running is useful for running effectiveness, where, following the acute effect of barefoot running compared to the shoe condition, runners improved power outputs such as form power, running effectiveness, leg stiffness and vertical oscillation (92). These retraining programs could generate adaptations in musculoskeletal structures that could affect running effectiveness in real race conditions, in the same way that short periods of barefoot running at comfortable speed have generated changes in the shod running at comfortable and high-speed running for these recreational runners, however, more research is needed.

Finally, there are some limitations to consider. First, the effect of two 10-week retraining programs has been studied on healthy recreational runners with low training load, we should be cautious about their effects on already injured runners or on experienced long-distance runners with a high training load. Secondly, although sagittal plane kinematics was the main concern, information about other planes of motion, ground reaction forces, joint moments or muscle activation remains unknown. And third, the effects of 10 weeks of retraining programs have been evaluated, but their long-term effects (e.g. a 12 months of follow-up), have not been assessed.

From a practical approach, both retraining programs could be useful in non-laboratory-based settings, using clinically feasible unsophisticated methods to generate changes in lower limb and trunk kinematics in recreational runners towards a running pattern that could reduce the mechanical risks of injury associated with excessive stress on the knee.

Conclusions

A progression of periods of barefoot running and a 10% cadence increase, both performed at a comfortable speed, showed an increase in knee and hip angle flexion and pelvic anterior tilt with a moderate to large effect size on comfortable running and high-speed running after 10 weeks. In addition, the progression of periods of barefoot running showed a significant reduction in ankle dorsiflexion and an increase in anterior trunk tilt with a small to moderate effect size at both speeds after the 10-week retraining program. This may be useful for reducing knee risk factors and increasing running efficiency, however more research is needed to explore the long-term effects.

STUDY 4. IS DYNAMIC FOOTPRINT AND BODY BALANCE AFFECTED BY BAREFOOT RUNNING OR BY THE 10% INCREASE IN CADENCE?

STUDY 4

Is dynamic footprint and body balance affected by barefoot running or by the 10% increase in cadence?

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Abstract

The purpose of the present study is to determine the effect of two different running retraining programs (periods of barefoot running and 10% increase of baseline cadence) on body balance and dynamic foot motion in recreational runners. This is a non-randomized controlled trial. Seventy-two endurance runners (30.0 ± 7.1 years old, 43% females) were allocated to a barefoot running group (BAR) (n = 23), a 10% increase cadence group (CAD) (n = 24), both with 3 sessions/week over 10 weeks, and a control group (CON) (n = 25) who did not perform any retraining. Body balance (i.e., centre of pressure [COP] area, length and velocity) and dynamics walking plantar pressure parameters (i.e., surface and areas by plantar zones, contact time and duration of rocker phases in gait) were measured with a plantar pressure platform before and after intervention. The postural balance tests were bipodal balance (eyes open [EO] and eyes closed [EC]), monopodal balance on dominant leg (EO and EC) and on non-dominant leg (EO and EC). ANCOVA was used to test differences between the BAR, CAD and CON post-intervention, adjusting for pre-intervention values. CAD group maintained their baseline body balance parameters, while BAR reduced COP length and velocity (mean groups' difference -144.05 mm and -10.80 mm/s, respectively) for non-dominant leg with EC. CON group maintained their baseline body balance parameters, while BAR reduced COP area, length and velocity (mean groups' difference -1227.01 mm2, -207.00 mm and -16.78 mm/s, respectively) for non-dominant leg with EC. A partial use of barefoot running in the recreational runners' training program of 3 sessions per week with a progressive increase in minutes resulted in improvements in body balance.

Keywords: postural stability, plantar pressure, barefoot running, increased step frequency

Introduction

Walking and running have been associated with humans since the earliest hominin evidence (1,2). Both walking, characterised by alternating bipodal and monopodal landings, and running, characterised by alternating monopodal supports and flight phases, have been suggested as two human capabilities by fossils from at least 4.4 million years ago (4) and 2 million years ago (5), respectively. Several hypotheses have been proposed linking these human locomotion capabilities to the evolution and survival of early hominids, especially for long distance running (4–6).

Nowadays, recreational runners' motivations for running are diverse, such as improving physical and mental health, achieving goals, obtaining tangible rewards, or because of social influences (8,9). Although, health is one of the reasons recreational runners between 26% and 74% will suffer a running-related injury in a one-year period (16–18), with an incidence of running-related injuries ranging from 2.5 to 33 injuries per 1,000 hours of running (20). Some of the biomechanical factors shown to be associated with increased risk of injury or decreased running economy have been decreased cadence, increased peak force at footstrike and a high prevalence of rearfoot strike (61,102,181,216).

Further variables related to injury prevention and performance improvement in runners are body balance and dynamic foot motion (328,329). Static body balance is a part of postural control related to increased lower limb force generation and the ability to rapidly restore body repositioning (330,331), which has been suggested to be associated with athletic success (331) as both a cause and consequence of injury in short distance running and other sports (332,333). Dynamic foot motion has been associated with foot structure (328), related to certain biomechanical dysfunctions and sports injuries (334,335).

Given these risk factors, one of the proven methods to increase cadence, reduce impact and decrease the prevalence of rearfoot strike has been a gradual transition to barefoot running (48,181,217). And similarly, increasing running cadence through direct biofeedback focusing on a 7.5% to 10% increase in cadence has been found to be a useful method of reducing impacts and the prevalence of rearfoot strike (45,258). However, the effects of barefoot running on body balance and dynamic foot movement are unclear

(157,220,221). Squadrone at al. (220) observed better body balance in the fully barefoot condition than when wearing socks for a static bipedal position. A recent study (157) demonstrated that running in minimalist shoes improves body balance and dynamic foot motion compared to wearing conventional running shoes. Nevertheless, an 8-week transition to barefoot running found no change for dynamic foot motion (221).

Additionally, no studies to date have assessed the effects of increasing cadence on body balance and dynamic foot movement. We have already studied the effects of providing biofeedback of a 10% increased cadence versus periods of barefoot running on foot strike angle, prevalence of rearfoot strike and spatiotemporal parameters such as cadence, stride length, contact time or flight time, in a homogeneous population group, after 10 weeks with a similar training load between these two retraining programs (48). However, the effects of these two retraining programs on body balance and dynamic foot movement in a homogeneous population group remain unknown.

Based on the aforementioned findings, the aim of the present study is to determine the effect of two different running retraining programs (periods of barefoot running and 10% increase of baseline cadence) on body balance and dynamic foot motion in recreational runners.

Methods and materials

Participants

A total of 110 recreational runners from amateur running clubs were interviewed. All subjects had to meet the following inclusion criteria; no injury or pain, regular participation in aerobic training at least three times per week for the past 2 years, and no history of injury in the previous six months that would limit training. Exclusion criteria were; no cardiorespiratory pathologies affecting cardiovascular performance, such as asthma, allergies, diabetes or other cardiac pathologies. This study was in accordance with the Declaration of Helsinki (2013) and was approved by the Ethics Committee of the University of Granada (no. 788/CEIH/2019). Prior to data collection, each runner was informed about the research and signed the informed consent form. Runners were assigned to three running retraining programs in a simple randomised approach; a barefoot running period group (BAR), a preferred cadence increase retraining group (CAD) and a control group (CON). **Figure 53** shows a flow diagram of participant recruitment. Participants who dropped out of the intervention were due to non-running related injuries (other recreational sports activities), personal reasons or failure to attend 85% of the retraining sessions. The entire study was conducted during the same season.

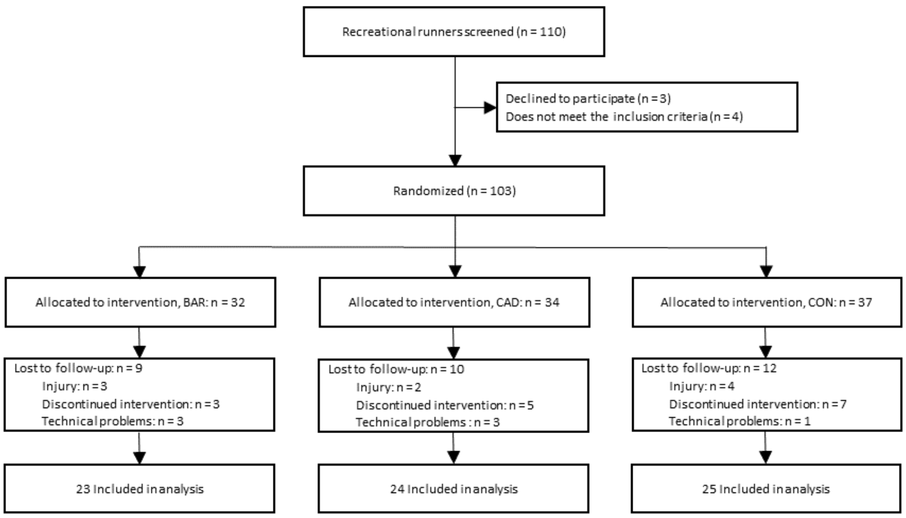


Figure 53. Representation of the recruitment of participants through a flow chart. BAR, Barefoot group; CAD, Cadence group; CON, Control group.

Materials and testing

For sample description, height and body weight were measured to the nearest 0.1 kg and 0.1 cm respectively (SECA Instruments, Germany), and body mass index (kg/m^2) was calculated. Fat mass and free-fat mass was measured using a bioimpedance test (Inbody 230, Inbody, Seoul, Korea). A 160 x 40 cm plantar pressure platform FreeMed® Professional (Sensormedica, Rome, Italy) was used, with a resolution of two sensors/cm^2 and a sampling frequency of 200 Hz, for both body balance and walking plantar pressure parameters. Body balance parameters were based on centre of pressures (COP); area (mm^2), length (mm) and velocity (mm/s). The parameters of plantar pressure during walking to assess dynamic foot motion were; Fick angle (degrees), surface area (mm^2) and load (percentage of total load) by nine plantar zones (such as hallux, 2nd-5th toe, 1st metatarsal head, 2nd-3rd metatarsal head, 4th-5th metatarsal head, medial arch, lateral arch, medial rearfoot and lateral rearfoot) (328), contact time (ms), and duration of walking rocker phases (percentage of contact time) (such as heel rocker, ankle rocker, forefoot rocker and toe rocker), all illustrated in **Figure 54**. Finally, the intra-runner natural running cadence (steps/min) before the intervention was recorded using a floor-based photocell system (Optogait; Microgate, Bolzano, Italy), mounted on a professional treadmill (Woodway Pro XL, Waukesha, WI, USA) at a sampling frequency of 1000 Hz, over a 2 min period (with more than 330 steps).

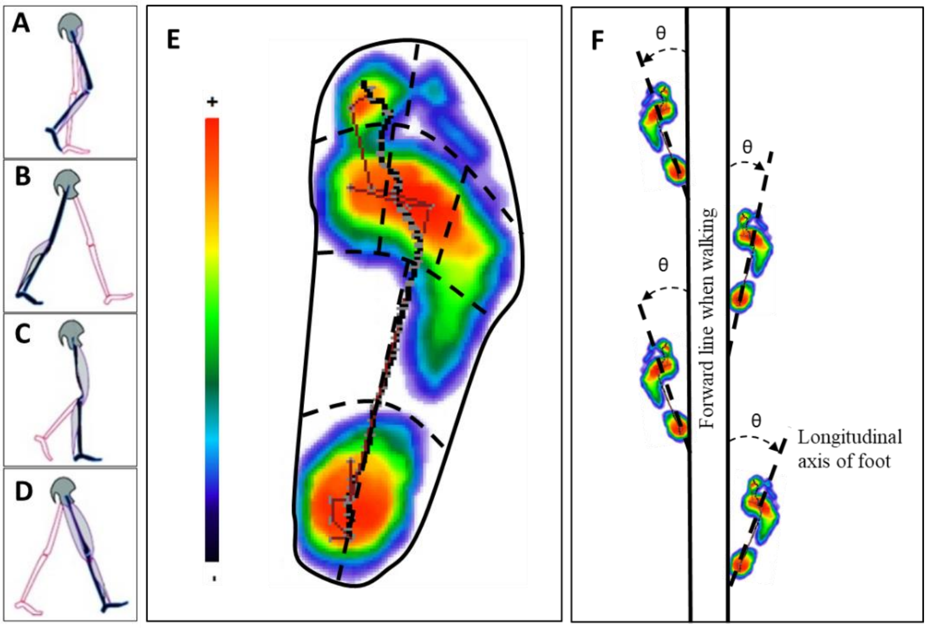


Figure 54. Graphical representation of the four walking rocker phases (A, toe rocker; B, forefoot rocker; C, ankle rocker; D, heel rocker), the nine zones of dynamic plantar pressures in E during walking (from top to bottom and left to right; hallux, 2nd-5th toes, 1st metatarsal head, 2nd-3rd metatarsal head, 4th-5th metatarsal head, medial arch, lateral arch, medial rearfoot and lateral rearfoot), and in F the Fick angle of the foot (θ denotes, Fick angle).

Procedures

Data collection began with recording the descriptive parameters of the sample (e.g., weight, height, age, BMI, fat mass and fat-free mass). This was followed by a 6-minute warm-up by walking on the plantar pressure platform along a 10-metre corridor. The only instruction given to the runners was: "walk at a comfortable speed, at a steady pace, and without stopping". After the walking warm-up, participants continued walking until at least 20 footprints (10 left and 10 right) were recorded, for the calculation of the dynamic plantar pressure parameters.

Then, the body balance testing protocol was performed consisting of three tests; 1) bipodal test (standing posture with self-selected foot position), 2) monopodal test with dominant leg, and 3) monopodal test with non-dominant leg (161). Each of the three tests was performed with eyes open and eyes closed, in this order. Regarding the order of starting with the dominant or non-dominant leg for the monopodal tests, a simple randomisation was carried out. The bipodal tests had a duration of 30 s with each condition, and the monopodal tests had a duration of 10 s (161), with hands-free position in all tests.

In order to establish the baseline natural cadence for the CAD group, a 10 min treadmill running protocol was carried out, with an 8 min warm-up, increasing the speed progressively to a comfortable speed self-selected by the participant and recording the baseline cadence for the remaining 2 min (48).

Running retraining programs

The runners' coaches and the principal investigator performed the retraining programs in person, to ensure that the runners adhered to the prescribed sessions. The BAR group performed barefoot retraining periods following a methodology previously published (48), and adapted from Latorre-Roman et al. (231). This consisted of the progressive inclusion of barefoot running on a soft, flat, grass or non-slip surface (i.e., a football pitch), mainly at a comfortable speed. The last weeks also included medium running speeds and progressive sets of sprints. The CAD group performed a retraining program based on a 10% increase of their natural cadence at comfortable speed determined pre-intervention. This group used a mobile app with metronome to provide auditory feedback of the 10% increased natural cadence (48). The CAD group was asked to strike their feet to the beat of the metronome and the running speed during the sessions was performed at comfortable speed. Both groups (BAR and CAD) performed a similar weekly load of retraining sessions with three sessions per week. On a weekly frequency, runners' attendance at the retraining sessions was monitored and they were asked about their perceived exertion using a score of 0-10 on the Borg scale (278). Finally, the CON group did not perform any retraining and the runners continued with their usual training load. All groups continued with their training loads and habits outside the retraining sessions, the BAR group used their running shoes, and the CAD group did not use a metronome (i.e., if they performed high-intensity sets on the track, if they performed long out-of-town runs or during competitions). Apart from the instructions described above, runners did not receive any other technical instructions. They were informed to decrease the intensity of training or even to stop training when pain or injury occurred during the intervention.

Statistical analysis

Prior to the statistical analysis, the 20 footprints (10 left and 10 right) were averaged for the parameters of the walking plantar pressures. To assess normal distribution and homogeneity in all data prior to analysis, Shapiro-Wilk and Levene tests were performed, respectively, showing that all data were suitable for parametric testing. To examine homogeneity for descriptive parameters (e.g., gender, age, weight, height, fat percentage, and muscle percentage) between experimental groups (i.e., BAR, CAD and CON groups) at baseline (pre-intervention), a chi-square test for dichotomous variables and a one-way analysis of variance (ANOVA) for continuous variables were performed. Descriptive data were reported in terms of means and standard deviations (SD). A one-way analysis of covariance (ANCOVA) was used to examine differences for body balance or walking plantar pressure variables (dependent variables) after 10 weeks of different running retraining programs, i.e., BAR group, CAD group, CON group (independent variables) at post-intervention. Baseline body balance or walking plantar pressure outcomes at pre-intervention were included as co-variate. Results from the ANCOVA were presented in mean difference, standard deviation (SD), and confidence interval (CI) of the difference. The effect sizes for group differences were expressed as Cohen's *d* (291); effect sizes are reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) (291). All data were analysed using SPSS for Windows Version 25.0 (Chicago, USA, IBM Corporation) and a significance level of $p \leq 0.05$ were applied.

Results

Among the 103 participants who started the study, 77 of them achieved 85% or more of the running retraining sessions, together with a perceived exertion of less than 3.6 out of 10 on the Borg scale. Finally, five were excluded due to analysis errors or outliers, thus a total of 72 recreational runners were included for analysis.

Table 17 shows the descriptive parameters by running retraining group and control group. No significant differences were found for gender, age, height, body weight and body mass index. Differences were observed for fat mass and fat-free mass, with the control group showing the lowest fat mass percentage and the highest fat mass percentage (all $P < 0.05$).

Table 17. Descriptive parameters of runners expressed as mean ± SD

Variable	BAR (n = 23)	CAD (n = 24)	CON (n = 25)	P value
Gender (percentage)	47.8 % females, 52.2% males	54.2% females, 45.8% males	28.0% females, 72.0% males	0.155
Age (year old)	31.6 ± 7.8	29.5 ± 6.3	28.8 ± 7.2	0.396
Height (cm)	173.3 ± 11.7	172.5 ± 7.3	173.81 ± 6.9	0.926
Body mass (kg)	71.7 ± 12.4	68.8 ± 11.2	70.2 ± 11.7	0.688
Body mass index (kg/m^2)	23.8 ± 3.2	23.0 ± 2.6	23.2 ± 2.8	0.578
Fat mass (percentage)	23.2 ± 9.7	20.5 ± 5.9	17.0 ± 5.2	**0.015**
Fat-free mass (percentage)	44.0 ± 5.0	44.5 ± 3.8	46.9 ± 3.6	**0.037**

Abbreviations: SD, standard deviation; BAR, barefoot retraining group; CAD, cadence retraining group; CON, control group.

Results of one-way ANCOVA analyses to explore post-intervention differences between running retraining programs for walking plantar pressure variables during walking protocol, adjusting for pre-intervention values, are shown in **Table 18**. The BAR group showed; a significant reduction of the relative load in the 2nd-5th toes area (large effect size, Cohen's d 1.084), and in the head of the 4th-5th metatarsal (large effect size, Cohen's d 1,619), compared to the CON group. The BAR group showed; a significant increase in both surface area and relative load in the 2nd-3rd metatarsal head area (large effect size, Cohen's d 0,936 and 0,898, respectively) compared to the CAD group. The remaining variables of dynamic plantar pressures during walking [i.e., a) flick angles, b) surfaces of; hallux, 2nd-5th toes, 1st metatarsal head, 4th-5th metatarsal head, medial arch, lateral arch, medial rearfoot and lateral rearfoot, c) loads of; hallux, 1st metatarsal head, medial arch, lateral arch, medial rearfoot and lateral rearfoot, and 4) duration of heel and ankle rockers] showed no changes between the different running re-education programs.

Table 18. Univariate ANCOVA between groups for dynamic plantar pressures during the walking protocol.

Variable	Groups		P-value	Mean Difference (SE)	CI of the Difference	
2^{nd}-3^{rd} metatarsal head surface (mm^2)	Barefoot	Cadence	**0.019***	2,57 (0,91)	0.33	4.81
	Barefoot	Control	0.435	1.33 (0.90)	-0.88	3.54
	Cadence	Control	0.486	-1.24 (0.88)	-3.38	0.91
2^{nd} to 5^{th} toes load (%)	Barefoot	Cadence	0,622	-0,43 (0,34)	-1,259	0,399
	Barefoot	Control	**0.043***	-0.85 (0.34)	-1.69	-0.02
	Cadence	Control	0,561	-0,42 (0,31)	-1,203	0,356
2^{nd}-3^{rd} metatarsal head load (%)	Barefoot	Cadence	**0.015***	3.28 (1.13)	0.50	6.05
	Barefoot	Control	0,903	1,18 (1,14)	-1,603	3,968
	Cadence	Control	0,176	-2,09 (1,09)	-4,765	0,58
4^{th}-5^{th} metatarsal head load (%)	Barefoot	Cadence	0,774	-1,29 (1,13)	-4,058	1,483
	Barefoot	Control	**0.016***	-3.08 (1.07)	-5.71	-0.45
	Cadence	Control	0,257	-1,79 (1,03	-4,312	0,73

Note: Significant differences ($p < 0.05$) are highlighted in bold. *denotes p>0,05; **denotes p>0,001. ANCOVA, one-way analysis of covariance; SE, standard error; CI, confidence interval

Results of one-way ANCOVA analyses to explore post-intervention differences between running retraining programs for body balance variables, adjusting for pre-intervention values, are shown in **Figure 55** and **Table 19**. The bipodal balance tests (both eyes open and eyes closed conditions) showed no significant differences between groups. The monopodal tests with eyes open showed a significant reduction in COP area for the BAR group compared to the CAD and CON groups (moderate effect size, Cohen's d 0.680, for both comparisons) for the non-dominant leg condition, and for the BAR group compared to the CAD group (moderate effect size, Cohen's d 0.783) for the dominant leg condition. The monopodal test with eyes closed and non-dominant leg showed several significant changes of the BAR group compared to the other two experimental groups; a significant reduction of the COP area compared to the CON group (moderate effect size, Cohen's d 0.598), a significant reduction of the COP length compared to the CAD group and CON group (moderate and large effect sizes, Cohen's d 0.681 and 0.856, respectively), and a significant reduction of the COP velocity compared to the CAD and CON groups (small and moderate effect size, Cohen's d 0.366 and 0.573, respectively). Lastly, the monopodal test with eyes closed and dominant leg showed a significant decrease in the COP length of the BAR group compared to the CON group (moderate effect size, Cohen's d 0.514).

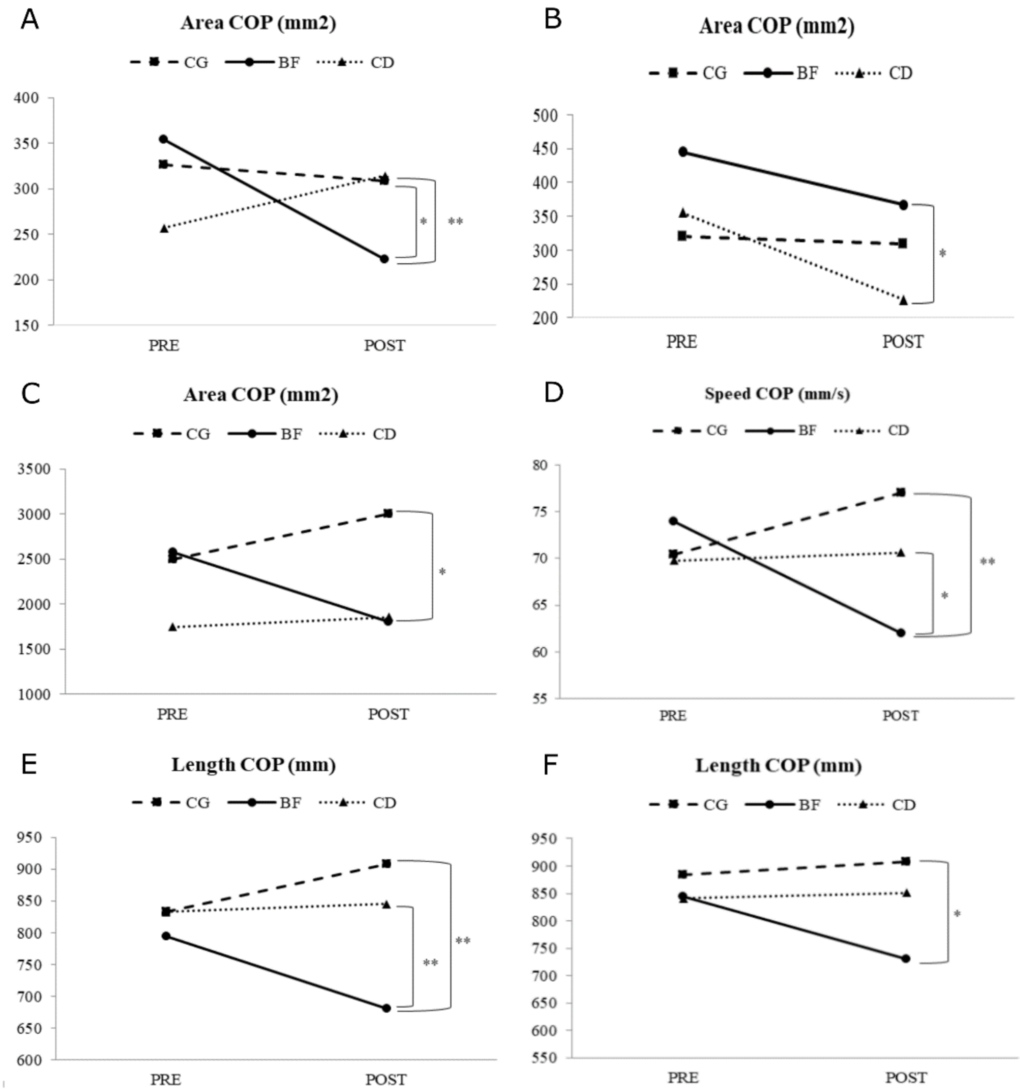


*Figure 55. Monopodal body balance parameters; A, non-dominant leg eyes open, B, dominant leg eyes open, C, D and E, non-dominant leg eyes close, D, dominant leg eyes close. Abbreviations; CG, control group, BF, barefoot group, CD, increased cadence group. *denotes p<0.05, **denotes p<0.001.*

Table 19. Univariate ANCOVA between experimental groups for the body balance protocol

Condition	Variable	Groups		P-value	Mean Difference (SE)	CI of the Difference	
Bipodal open eyes	COP area (mm^2)	Barefoot	Cadence	0.841	7.27 (36.1)	-64.9	79.4
		Barefoot	Control	0.087	-61.80 (35.6)	-132.9	9.3
		Cadence	Control	0.051	-69.07 (34.8)	-138.4	0.3
	COP length (mm)	Barefoot	Cadence	0.888	10.41 (73.8)	-137.0	157.8
		Barefoot	Control	0.932	-6.21 (73.0)	-152.0	139.5
		Cadence	Control	0.820	-16.63 (72.7)	-161.7	128.4
	COP velocity (mm/s)	Barefoot	Cadence	0.859	-0.45 (2.5)	-5.5	4.6
		Barefoot	Control	0.942	-0.18 (2.5)	-5.2	4.8
		Cadence	Control	0.914	0.27 (2.5)	-4.7	5.2
Bipodal closed eyes	COP area (mm^2)	Barefoot	Cadence	0.323	-49.07 (49.2)	-147.3	49.2
		Barefoot	Control	0.124	-74.91 (48.1)	-171.0	21.2
		Cadence	Control	0.582	-25.83 (46.7)	-119.1	67.4
	COP length (mm)	Barefoot	Cadence	0.514	58.36 (89.0)	-119.2	235.9
		Barefoot	Control	0.328	87.79 (89.1)	-90.0	265.5
		Cadence	Control	0.738	29.43 (88.0)	-145.7	204.6
	COP velocity (mm/s)	Barefoot	Cadence	0.505	1.99 (3.0)	-3.9	7.9
		Barefoot	Control	0.315	3.01 (3.0)	-2.9	8.9
		Cadence	Control	0.729	1.02 (2.9)	-4.8	6.9
Non-dominant leg. open eyes	COP area (mm^2)	Barefoot	Cadence	**0.006****	-103.00 (36.4)	-175.6	-30.4
		Barefoot	Control	**0.015***	-89.27 (35.8)	-160.6	-17.9
		Cadence	Control	0.700	13.73(35.5)	-57.1	84.6
	COP length (mm)	Barefoot	Cadence	0.617	17.80 (35.4)	-52.9	88.4
		Barefoot	Control	0.610	-17.76 (34.7)	-86.9	51.4
		Cadence	Control	0.304	-35.56 (34.3)	-104.1	33.0
	COP velocity (mm/s)	Barefoot	Cadence	0.656	1.51 (3.4)	-5.2	8.2
		Barefoot	Control	0.757	-1.02 (3.3)	-7.6	5.6
		Cadence	Control	0.443	-2.54 (3.3)	-9.1	4.0
Dominant leg. open eyes	COP area (mm^2)	Barefoot	Cadence	**0.011***	-125.74 (47.8)	30.4	221.1
		Barefoot	Control	0.430	37.72 (47.5)	-57.1	132.6
		Cadence	Control	0.063	-88.02 (46.6)	-181.0	5.0
	COP length (mm)	Barefoot	Cadence	0.524	-15.10 (23.6)	-62.2	32.0
		Barefoot	Control	0.497	-15.90 (23.3)	-62.3	30.5
		Cadence	Control	0.973	-0.80 (23.2)	-47.1	45.5
	COP velocity (mm/s)	Barefoot	Cadence	0.352	-1.91 (2.0)	-6.0	2.2
		Barefoot	Control	0.812	-0.48 (2.0)	-4.5	3.5
		Cadence	Control	0.478	1.43 (2.0)	-2.6	5.4
Non-dominant leg. closed eyes	COP area (mm^2)	Barefoot	Cadence	0.477	-342.26 (478.4)	-1296.8	612.3
		Barefoot	Control	**0.011***	-1227.01 (468.3)	-2161.5	-292.5
		Cadence	Control	0.63	-884.75 (467.7)	-1818.0	48.5
	COP length (mm)	Barefoot	Cadence	**0.009****	-144.05 (53.8)	-251.5	-36.6
		Barefoot	Control	**0.000****	-207.00 (53.3)	-313.4	-100.6
		Cadence	Control	0.236	-62.95 (52.7)	-168.0	42.1
	COP velocity (mm/s)	Barefoot	Cadence	**0.041***	-10.80 (5.2)	-21.2	-0.4
		Barefoot	Control	**0.002****	-16.78 (5.1)	-27.0	-6.5
		Cadence	Control	0.243	-5.98 (5.1)	-16.1	4.2
Dominant leg. closed eyes	COP area (mm^2)	Barefoot	Cadence	0.669	-420.58 (979.1)	-2374.3	1533.2
		Barefoot	Control	0.934	82.30 (982.6)	-1878.5	2043.1
		Cadence	Control	0.597	502.87 (945.8)	-1384.4	2390.2
	COP length (mm)	Barefoot	Cadence	0.122	-122.53 (78.2)	-278.7	33.6
		Barefoot	Control	**0.047***	-157.06 (77.6)	-311.8	-2.3
		Cadence	Control	0.654	-34.54 (76.7)	-187.6	118.6
	COP velocity (mm/s)	Barefoot	Cadence	0.256	-8.69 (7.6)	-23.8	6.4
		Barefoot	Control	0.784	-2.10 (7.6)	-17.3	13.1
		Cadence	Control	0.374	6.58 (7.4)	-8.1	21.3

Note: Significant differences ($p < 0.05$) are highlighted in bold. *denotes p>0,05; **denotes p>0,001. Abbreviations: ANCOVA, one-way analysis of covariance; SE, standard error; CI, confidence interval; COP, centre of pressures.

Discussion

This study sought to determine the effect of both promoting a 10% increase in cadence and a progression of barefoot running periods on body balance and dynamic walking foot motion in recreational endurance runners after a 10-week period. The primary finding of this study was that the barefoot running retraining program compared to the other groups showed changes on body balance with moderate effect size, mainly for the leg in the monopodal eyes-closed, non-dominant leg condition. Secondarily, this study found no effective changes for either of the two retraining programs in dynamic walking foot motion, related to foot structure (328). As far as we are aware, this is the first study to assess the effect of these two retraining programs on postural balance and dynamic foot motion in a similar cohort of recreational endurance runners.

Numerous previous studies have shown similar findings regarding several running biomechanics between barefoot running (48,181,217) and increasing basal cadence (45,258), such as, increasing cadence, reducing impact, and decreasing the prevalence of rearfoot strike. Likewise, our initial findings for the present experimental design showed that both running retraining programs increased cadence and reduced foot angle at the footstrike (48). However, according to the findings of the present study, differences related to body balance could be observed between a transition program using periods of barefoot running and increased cadence. Specifically, the BAR group showed significant reductions for body balance parameters (i.e., COP area, length and velocity) compared to both the CAD and CON groups that maintained their baseline values. During a static body balance test, the reduction of COP disturbances is associated with improved performance in terms of the athlete's postural control, such as a reduction in the area, length and velocity of the COP (336). Thus, the BAR group experienced an improvement in static test performance compared to the CAD and CON groups, in particular with monopodal support and eyes closed.

Especially, the monopodal support with eyes closed and non-dominant leg was the test that showed the most significant changes for the BAR group compared to the CAD group (i.e., COP length and velocity) and CON group (i.e., COP area and velocity). According to Skelton et al. (337) the non-dominant leg is considered the leg of support and stability, therefore, this leg may have generated more changes than the dominant leg, improving body balance more effectively. The greater presence of significant changes observed in the monopodal test compared to the bipodal test, and eyes closed compared to eyes open could be caused by the increased demand of the physical task. Kelly et al. (338) found that increasing the difficulty of postural balance tests increased muscle activation of the plantar intrinsic foot muscles.

Our results are in agreement with those of Squadrone et al. (220) and Cudejko et al. (157). The findings of Squadrone at al. (220) indicated that wearing footwear that simulates being barefoot (i.e. minimalist shoes) has a better sense of the static and dynamic position of the ankle compared to wearing conventional footwear. Similarly, Cudejko et al. (157) showed that minimalist shoes improves dynamic stability and physical walking function compared to conventional shoes. However, these are all studies examining the effect of minimalist footwear on body stability, the present study compares body stability with a transition to barefoot running periods. The benefits of barefoot running on these outcomes could be explained by a demonstrated increase in plantar intrinsic foot muscle activation increased by running barefoot (338), which when implemented over a specialised period and dose of work could produce changes in recreational endurance runners. Improvements in postural balance have been associated with improved coordination and pre-activation of the dominant lower limb musculature prior to the footstrike (85,90), which has been suggested as the cause of improved running economy (339).

The authors believe that not only an increase in cadence or a transition to forefoot strike could be the cause of an increase in body balance, but also a combination of the reduction of the midsole thickness of the shoe or barefoot running. This hypothesis could be supported by those studies that without a full immersion into barefoot running already experienced an improvement in postural balance (157,220). Moreover, a recent study evaluating different shoe thicknesses showed that a progressive reduction in midsole thickness leads to an increase in static body stability (340). And this may explain why neither the CAD nor the CON group experienced changes in body balance, as at no point during the retraining program they were allowed to exercise or run barefoot.

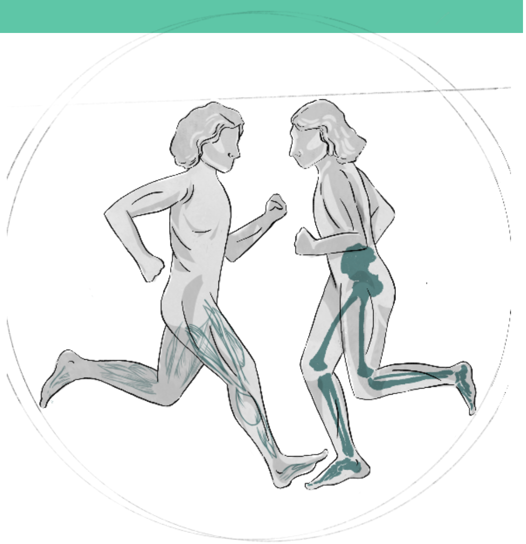
Regarding dynamic foot motion, Hillstrom et al. (328) observed relationships between plantar pressure by area and foot type. According to our findings, little evidence indicates clear structural changes after 10 weeks of running retraining for both programs. According to these authors, flat feet present high plantar pressures in the region of the hallux, 2^{nd}-3^{rd} toes, and 2^{nd} metatarsal head. However, our findings showed no changes for the hallux either in surface or plantar loading. Besides, BAR group showed a lower load for the 2^{nd}-5^{th} toes area and for the 4^{th}-5^{th} metatarsal head compared to CON group that maintained their baseline values, evidencing a lower lateral load for the BAR group. Miller et. al (167) suggest that running with midsole thicknesses less than 4mm or barefoot increases the use of the spring function of the plantar arch (i.e., abductor hallucis, flexor digitorum brevi, and abductor digiti minimi), increasing the demand on the intrinsic foot musculature and thus strengthening the foot.

A potential weakness of this study was that only plantar footprints were analysed for dynamic foot mobility; the use of other systems (e.g. video analysis) could have provided information about the foot or ankle. In addition to the time spent training in retraining sessions, runners could run in their own running shoes, the fact that the type of footwear was not controlled during training could be another weakness of the study.

Conclusion

A partial use barefoot running in the recreational runners' training program of 3 sessions per week with a progressive increase in minutes resulted in improvements in body balance. Increasing cadence by 10% could lead to changes in running biomechanics (48), but no changes have been observed for body balance or dynamic foot movement. From a practical approach, both coaches and clinicians could benefit for practical purposes from retraining sessions with periods of barefoot running as a tool and not an end, with the aim of improving the balance skills of recreational endurance runners, while respecting loading and resting periods in safe surfaces (e.g., soft, flat, and grass or non-slip surface).

CAPÍTULO 5. CONCLUSIONES



5.1. LIMITACIONES

SECCIÓN 1: *Evaluación biomecánica de la carrera en situación real de competición.*

La principal limitación de esta sección ha sido no proporcionar variables sociodemográficas y antropométricas, que podrían haber ayudado a la comprensión de los resultados durante la discusión. En segundo lugar, el análisis del tipo de pisada mediante análisis visual de vídeo podría ser otra limitación, ya que es menos preciso que un sistema de captura de movimiento en 3D. Por último y tercera limitación, no se controló, ni evaluó el tipo de calzado de los corredores, que podría ser una variable contaminante de los parámetros cinemáticos de estudio.

A pesar de estas limitaciones, la metodología usada el a presente sección ha permitido incluir una gran muestra poblacional de corredores, por lo que estos resultados proporcionan una elevada potencia estadística.

SECCIÓN 2: E*ficacia de dos programas de reeducación de la técnica de carrera para corredores amateurs de larga distancia.*

Aunque esta sección considera el efecto de dos programas de reeducación de la técnica de carrera de 10 semanas en corredores amateurs sanos, la extrapolación de estos resultados a corredores lesionados, de élite, juveniles o de competición de larga distancia debe hacerse con precaución, y sus efectos en corredores ya lesionados no ha sido estudiada.

Debido al pequeño tamaño de la muestra del presente estudio, no fue posible analizar los efectos de los programas de reeducación de la técnica de carrera por sexos, tal como si fue posible en la sección 1.

La cadencia que presentaron los corredores fue relativamente alta al inicio del estudio (166 pasos/min y 180 pasos/min en cada velocidad), lo que dificulta el aumento del 10% fijado por el estudio (183 pasos/min y 198 pasos/min).

El efecto de los dos programas de reeducación de la técnica de 10 semanas se ha estudiado en corredores amateurs con una carga de entrenamiento baja, por lo que debemos ser cautos sobre sus efectos en corredores experimentados o de élite con una alta a carga de entrenamiento.

Aunque la cinemática del plano sagital era la principal preocupación, se desconoce la información sobre otros planos de movimiento, las fuerzas de reacción del suelo, los momentos articulares o la activación muscular.

Se han evaluado los efectos de 10 semanas de dos programas de reeducación de la técnica de carrera en entornos ecológicos sin uso de tecnologías de alto coste, pero no se ha evaluado el hecho de que sus efectos sean mantenidos a largo plazo. Por ejemplo, mediante un seguimiento de 6 meses o incluso de 12 meses.

Con este diseño experimental se ha podido observar los cambios tras las 10 semanas de aplicar los dos programas de reeducación de la técnica de carrera (pre-test y post-test). Pero no se ha hecho un seguimiento diario o semanal de los cambios producidos durante el trascurso del programa de reeducación. Es decir, una monitorización continuada en el tiempo, para dar a conocer como los corredores amateurs van generando el aprendizaje motor del nuevo patrón de carrera durante la aplicación de los programas de reeducación.

Un punto débil potencial de este estudio fue que sólo se analizaron las huellas plantares para determinar la movilidad dinámica del pie; el uso de otros sistemas (por ejemplo, el análisis de vídeo) podría haber proporcionado información sobre el pie o el tobillo. Además del tiempo dedicado al entrenamiento en las sesiones de readaptación, los corredores podían correr con sus propias zapatillas, el hecho de que no se controlara el tipo de calzado durante el entrenamiento podría ser otro punto débil del estudio.

5.3. CONCLUSIONES GENERALES

SECCIÓN 1: *Evaluación biomecánica de la carrera en situación real de competición.*

Los hallazgos sugieren que mantener un apoyo adelantado, no aumentar el tiempo de contacto y no disminuir el tiempo de vuelo podría ser beneficioso para mejorar el rendimiento durante una carrera de larga distancia en los últimos kilómetros.

SECCIÓN 2: *Eficacia de dos programas de reeducación de la técnica de carrera para corredores amateurs de larga distancia.*

Tras 10 semanas de los programas de reeducación de carrera basada en periodos de carrera descalza y aumento de un 10% de la cadencia basal se observaron cambios compartidos (disminución del ángulo del pie en el contacto inicial, aumento de la flexión de rodilla, cadera y mayor inclinación anterior de pelvis). Aunque hay que destacar que el programa de periodos de carrera descalza mostró cambios (reducción de la prevalencia de apoyos retrasados, disminución de la longitud de paso, reducción del ángulo de flexión dorsal de tobillo en el contacto inicial, aumento la inclinación anterior de tronco y cambios en el equilibrio postural), que por el contrario el aumento de cadencia de un 10% no mostró.

5.4. CONCLUSIONES ESPECÍFICAS

SECCIÓN 1: *Evaluación biomecánica de la carrera en situación real de competición.*

- Los resultados demostraron una alta prevalencia de apoyos retrasados para la mayoría de los corredores analizados.
- La prevalencia de apoyos retrasados aumentó del km 5 al km 15 sólo para el grupo de los hombres, en aquellos corredores cuya clasificación empeoró entre los dos kilometrajes.
- Los parámetros espaciotemporales se vieron afectados por el sexo, ya que las mujeres aumentaron el tiempo de contacto y redujeron tiempo de vuelo, respectivamente, con el trascurso de la competición (desde el km 5 hasta el km 15).
- Aquellos corredores que mejoraron su posición de carrera del km5 al km15 redujeron el tiempo de contacto y aumentaron el tiempo de vuelo.

SECCIÓN 2: *Eficacia de dos programas de reeducación de la técnica de carrera para corredores amateurs de larga distancia.*

- El ángulo del pie en el contacto inicial disminuyó para ambos programas de reeducación de la técnica, periodos de carrera descalza (BAR) y aumento de la cadencia basal de un 10% (CAD). Con un tamaño del efecto moderado.
- La prevalencia de apoyo retrasado únicamente fue reducida por el grupo BAR tras las 10 semanas de intervención. Con un tamaño del efecto moderado.
- La cadencia aumentó significativamente para el grupo CAD a velocidad confortable, del mismo modo que lo hizo para el grupo BAR a alta velocidad de carrera. Con un tamaño del efecto pequeño.
- Por el contrario, la longitud de paso disminuyó significativamente únicamente para el grupo BAR a alta velocidad de carrera. Con un tamaño del efecto pequeño.
- El tiempo de aterrizaje disminuyó a velocidad confortable para ambos grupos, BAR y CAR. Y únicamente se redujo para el grupo BAR a alta velocidad de carrera. Con un tamaño del efecto moderado.

- En cuanto a la cinemática articular de miembros inferiores, ambos programas de reeducación de la técnica de carrera (BAR y CAD) mostraron un aumento del ángulo de flexión de rodilla y de flexión de cadera, y además de inclinación anterior de la pelvis tanto a velocidad confortable como alta. Con un tamaño del efecto de moderado a grande.
- Únicamente el grupo BAR redujo significativamente la flexión dorsal de tobillo en el contacto inicial, y aumento la inclinación anterior de tronco en ambas velocidades. Con tamaños del efecto de pequeños a moderados.
- Inversamente, el grupo CON disminuyó la cadencia, aumentó la longitud de paso, y aumentó el ángulo de extensión de cadera, la inclinación posterior de la pelvis y la inclinación posterior del tronco con un tamaño del efecto entre pequeño y moderado.
- Un uso no inmersivo de la carrera descalza en el programa de entrenamiento de corredores amateurs de 3 sesiones semanales con un aumento progresivo de minutos produjo mejoras en el equilibrio corporal.
- Tras el programa de reeducación de la carrera para aumentar la cadencia en un 10% no se han observado cambios en el equilibrio corporal ni en el movimiento dinámico del pie.
- Ninguno de los dos programas de reeducación técnica produjo cambios claros en las huellas plantares, que podría haber derivado en cambios estructurados en la musculatura intrínseca del pie.

5.5. APLICACIONES PRÁCTICAS

SECCIÓN 1: *Evaluación biomecánica de la carrera en situación real de competición.*

Los resultados de la presente sección de la Tesis Doctoral son útiles para caracterizar una carrera real de larga distancia sobre corredores populares de fondo, concretamente durante una media maratón, siendo esta información de utilidad para que los atletas y los entrenadores comprendan mejor cómo el patrón o tipo de pisada (en inglés; *"footstrike pattern"*) podría influir en el rendimiento del corredor y en el riesgo de lesiones.

Las diferencias significativas entre el tipo de pisada y los parámetros espaciotemporales según el sexo y los cambios de posición en la carrera, sugeridas por esta sección, suponen una contribución original al análisis biomecánico de la carrera de resistencia desde un paradigma ecológico (fuera del laboratorio). Sin embargo, no puede determinar con precisión si los corredores más experimentados y bien entrenados, la fatiga o el control del ritmo son responsables de los cambios en el tipo de pisada y de los parámetros espaciotemporales durante la carrera.

SECCIÓN 2: *Eficacia de dos programas de reeducación de la técnica de carrera para corredores amateurs de larga distancia.*

Los hallazgos de la sección 2 de la presente Tesis Doctoral son de utilidad para conocer los efectos de 10 semanas de; 1) periodos de carrera descalza y 2) aumento de la cadencia de un 10% mediante feedback el uso de un metrónomo, sobre la técnica de carrera para corredores, entrenadores y otros especialistas de la salud que traten con corredores amateurs.

Hasta la fecha, poco se conoce sobre los efectos biomecánicos (cinemática del pie, articular, tronco y parámetros espaciotemporales) de los programas de reeducación de carrera en entornos ecológicos (fuera de laboratorio), sin el uso de tecnologías sofisticadas o de alto coste, y viables para ser ejecutadas por entrenadores o clínicos sobre corredores amateurs.

A pesar de los efectos prometedores de sesiones de reeducación de carrera agudas basados en el laboratorio con la finalidad de reducir los picos de impacto y la carga en miembros inferiores hacia la prevención de lesiones en carrera (45,119,120,122,255,260,321). Varios estudios previos han demostrado que los cambios en los patrones de carrera asociados a la una pisada de antepié y el aumento de la cadencia reducen la atenuación del impacto tras los programas de reeducación de la técnica de carrera (45,46,119–122,260). Otros estudios sugieren que correr descalzo fomenta una reducción del apoyo retrasado o talonador que podría reducir la fuerza de reacción del suelo y las tasas de carga (en inglés; *"loading rate"*) en los corredores amateurs (181,217). Por ello, tanto el aumento de la cadencia como la carrera descalza han sido hipotetizadas como alternativas clínicamente válidas, aplicables en campo y ecológicas, para reducir el riesgo de lesiones (102,181,216).

Dicho esto, los hallazgos de la **SECCIÓN 2** demuestran dos programas para la reeducación técnica eficaces para generar cambios en la biomecánica del corredor, con el objetivo de reducir la prevalencia de apoyos retrasados, reducir el ángulo del pie en el contacto inicial, aumentar el ángulo de rodilla y cadera, siguiendo una progresión de cargas saludable para corredores amateurs de 10 semanas, y sin usar tecnologías sofisticadas o de alto coste, aplicables en entornos naturales o ecológicos (fuera del laboratorio).

El programa de 10 semanas de aumento de la cadencia basal en un 10% mostró cambios más conservadores, y si además tenemos en consideración que el programa se ejecuta con el calzado de los corredores amateurs. Se puede sugerir que podría ser de utilidad en aquellos corredores que busquen un programa de la reeducación más protector y conservador. Además, podría permitir el uso de ortesis plantares ya que se realiza calzado en todo momento. Aunque sus efectos en patología no han sido estudiamos, por lo que esta aplicación debería ser entendida con especial cautela.

Por ello, estos hallazgos pretenden ser de utilidad hacía fines prácticos o de campo (fuera de los laboratorios), por ejemplo, en entornos deportivos para corredores, entrenadores o educadores físicos, pero también en entornos clínicos para médicos deportivos, fisioterapeutas u otros clínicos que trabajen con corredores amateurs. Ambos programas podrían reducir los factores de riesgo de la rodilla y aumentar la eficiencia de la carrera. Aunque también se necesita más investigación para explorar los efectos a largo plazo.

Tanto los entrenadores como los clínicos podrían beneficiarse a efectos prácticos de sesiones de reeducación de la técnica con periodos de carrera descalza como herramienta y no como fin, con el objetivo de mejorar las capacidades de equilibrio de los corredores de resistencia amateur, respetando los periodos de carga y descanso en superficies seguras (por ejemplo, blandas, planas y con hierba o superficie antideslizante).

5.2. PERSPECTIVAS DE FUTURO

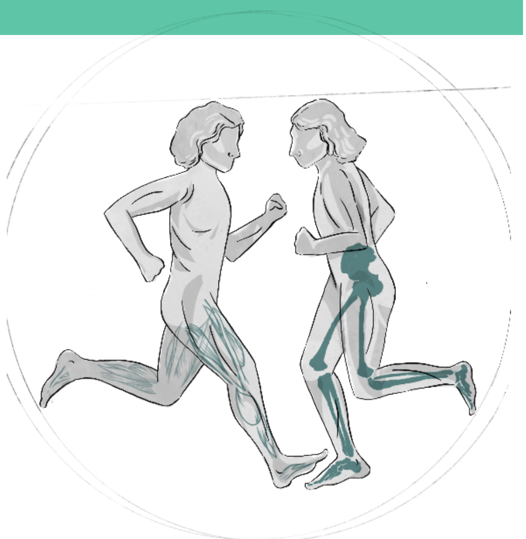
La presente Tesis Doctora ha evaluado el patrón de pisada, la inversión y las variables espaciotemporales de una amplia muestra de corredores de resistencia durante una carrera de fondo en carretera, en función del sexo, en dos puntos (km5 y km15) de una carrera real de larga distancia, sin embargo sería conveniente profundizar en el conocimiento de como interactúan parámetros biomecánicos y fisiológicos intra-corredores monitorizando en periodos de tiempo más cortos (por ejemplo, cada kilómetro de la carrera). Un estudio usando wearables portables durante una competición real podría aportar una amplia información sobre los parámetros biomecánicos y fisiológicos de la carrea y el rendimiento de los corredores de resistencia.

Igualmente, para la Sección 2 se han examinado los cambios producidos tras 10 semanas de reeducación de la técnica de carrera antes y después de llevar a cabo la intervención. El uso de sensores portables, wearables, podría aportar conocimiento sobre como los corredores evolucionan o modifican su biomecánica de carrera, generando datos semanales incluso diarios de cada corredor de larga distancia.

El conocimiento de la biomecánica del calzado y la biomecánica de la carrera nos ha demostrado que están relacionadas y parámetros como el tipo de pisada, el tiempo de contacto, la longitud de paso, las fuerzas de reacción del suelo y cinemática y momentos angulares puedes ser modificados. Sin embargo, el estudio del efecto del calzado y la interacción con los dos programas de reeducación de la técnica planteados no se estudiaron en la presente Tesis Doctoral, con lo cual, con la finalidad de profundizar en los efectos de la reeducación de la carrera y la biomecánica de carrera se podría incluir la clasificación y descripción de las características biomecánicas en futuras líneas de investigación.

El conocimiento aportado tras llevar a cabo 10 semanas de los programas de reeducación de carrera basada en periodos de carrera descalza y aumento de un 10% de la cadencia basal han demostrados que existen cambios compartidos entre ambos programas, como la disminución del ángulo del pie en el contacto inicial, el aumento de la flexión de rodilla, cadera y mayor inclinación anterior de pelvis en población sana. Estos hallazgos han sido sugeridos por diversos autores y discutidos en la presente Tesis Doctoral con posibles asociaciones para reducir los factores de riesgo de lesión y mejorar la economía de carrera. Sin embargo, los efectos sobre poblaciones especiales (por ejemplo, corredores de anciana edad, embarazadas o adolescentes) o lesiones (dolor de rodilla anterior, tendinitis rotuliana o tendinitis aquílea) siguen sin ser estudiados. Además, la población estudiada y descrita fueron corredores amateurs, con lo cual sus efectos sobre corredores de élite y alto nivel también son desconocidos. Por lo tanto, más investigación sería necesaria en estos grupos poblacionales con la finalidad de profundizar los efectos de la carrera descalza o el aumento del 10% de la cadencia en diversos tipos de población.

CHAPTER 5. CONCLUSIONS



5.1. LIMITATIONS

SECTION 1: *Biomechanical running assessment in a real competition situation.*

The main limitation of this section was not providing sociodemographic and anthropometric variables, which could have helped the understanding of the results during the discussion. Secondly, the analysis of stride type by visual video analysis could be another limitation, as it is less accurate than a 3D motion capture system. The third and final limitation, the type of footwear of the runners, which could be a contaminating variable of the kinematic parameters of the study, was not controlled or evaluated.

Despite these limitations, the methodology used in this section has allowed the inclusion of a large population sample of runners, so these results provide a high statistical power.

SECTION 2: *Effectiveness of two running retraining programs for recreational long-distance runners.*

Although this section considers the effect of two 10-week running retraining programs on healthy recreational runners, extrapolation of these results to injured, elite, youth or long-distance competitive runners should be made with caution, and their effects on already injured runners have not been studied.

Due to the small sample size of the present study, it was not possible to analyse the effects by gender, as was possible in section 1.

The cadence presented by the runners was relatively high at the start of the study (166 steps/min and 180 steps/min at each speed), which hinders the 10% increase set by the study (183 steps/min and 198 steps/min).

The effect of the two 10-week retraining programs has been studied in amateur runners with a low training load, so we should be cautious about their effects in experienced or elite runners with a high training load.

Although sagittal plane kinematics was the main concern, information on other planes of motion, ground reaction forces, joint moments or muscle activation is unknown.

The effects of 10 weeks of retraining programs have been evaluated, but their long-term effects (e.g., 12-month follow-up) have not been assessed.

A potential weakness of this study was that only footprints were analysed to determine the dynamic mobility of the foot; the use of other systems (e.g. video analysis) could have provided information about the foot or ankle. In addition to the time spent training in the retraining sessions, runners were allowed to run in their own shoes, the fact that the type of footwear was not monitored during training could be another weakness of the study.

5.3. GENERAL CONCLUSIONS

SECTION 1: *Biomechanical running assessment in a real competition situation.*

The findings suggest that maintaining a forefoot strike, not increasing contact time, and not decreasing flight time may be beneficial in improving performance during a long-distance race in the final kilometres.

SECTION 2: *Effectiveness of two running retraining programs for recreational long-distance runners.*

After 10 weeks of the running retraining programs based on barefoot running periods and a 10% increase in baseline cadence, shared changes were observed (decreased foot angle at initial contact, increased knee and hip flexion and greater anterior pelvic tilt). Although it should be noted that the periods of barefoot running program (reduction in the prevalence of rearfoot strikes, decrease in stride length, reduction in the angle of dorsiflexion of the ankle at initial contact, increase in anterior trunk tilt and changes in postural balance), whereas the 10% increase in cadence did not.

5.4. SPECIFIC CONCLUSIONS

SECTION 1: *Biomechanical running assessment in a real competition situation.*

- The results showed a high prevalence of rearfoot strikes for most of the runners analysed.
- The prevalence of rearfoot strikes increased from km 5 to km 15 only for the men's group, in those runners whose ranking worsened between the two kilometres.
- The spatiotemporal parameters were affected by gender, with females increasing contact time and decreasing flight time, respectively, over the course of the competition (from km 5 to km 15).
- Those runners who improved their running position from km 5 to km 15 reduced contact time and increased flight time.

SECTION 2: *Effectiveness of two running retraining programs for recreational long-distance runners.*

- Foot angle at initial contact decreased for both retraining programs, periods of barefoot running (BAR) and increased basal cadence by 10% (CAD). With a moderate effect.
- The prevalence of delayed support was only reduced by the BAR group after the 10-week intervention. Moderate effect.
- Cadence increased significantly for the CAD group at comfortable speed, as it did for the BAR group at high running speed. With a small effect.
- In contrast, stride length decreased significantly only for the BAR group at high running speed. With a small effect.

- Landing time decreased at comfortable speed for both BAR and CAR groups. And it decreased only for the BAR group at high running speed. With a moderate effect.

- In terms of lower limb joint kinematics, both running technique re-education programs (BAR and CAR) showed an increase in knee flexion angle and hip flexion angle, as well as anterior pelvic tilt at both comfortable and high speed. With a moderate to large effect.

- Only the BAR group significantly reduced dorsal ankle flexion at initial contact and increased anterior trunk tilt at both speeds. With small to moderate effects.

- Conversely, the CON group decreased cadence, increased stride length, and increased hip extension angle, posterior pelvic tilt and posterior trunk tilt with small to moderate effects.

- A non-immersive use of barefoot running in the recreational runners' training program of 3 sessions per week with a progressive increase in minutes resulted in improvements in body balance.

- Following the running retraining program to increase cadence by 10%, no changes in body balance or dynamic foot motion were observed.

- Neither of the two technical retraining programs produced clear changes in dynamic foot motion, which could have led to structured changes in the intrinsic musculature of the foot.

5.5. PRACTICAL APPROACH

SECTION 1: *Biomechanical running assessment in a real competition situation.*

The results of this section of the Doctoral Thesis are useful to provide a characterisation of a real event recreational long-distance runners, specifically during a half marathon, and this information is useful for both athletes and coaches to better understand how the footstrike pattern could influence the runner's performance and risk of injury.

The evidence of significant differences in footstrike pattern and spatiotemporal parameters by gender and changes in running position suggested by this section is an original contribution to the biomechanical analysis of endurance running from an ecological (out-of-laboratory) perspective. However, it cannot accurately determine whether more experienced and well-trained runners, fatigue or pace control are responsible for changes in stride type and spatiotemporal parameters during running.

SECTION 2: *Effectiveness of two running retraining programs for recreational long-distance runners.*

The findings in section 2 of this Doctoral Thesis are useful for understanding the effects of 10 weeks of; 1) periods of barefoot running and 2) increasing cadence by 10% through feedback using a metronome, on running technique for runners, coaches and other health specialists dealing with amateur runners.

To date, little is known about the biomechanical effects (kinematics of foot, joint, trunk and spatiotemporal parameters) of running re-education programs in ecological (non-laboratory) settings, without the use of sophisticated or high-cost technologies, and feasible for implementation by coaches or clinicians on amateur runners.

Despite the promising effects of acute laboratory-based running re-education sessions aimed at reducing peak impact and lower limb loading towards the prevention of running injuries (45,119,120,122,255,260,321). Several previous studies have shown that changes in running patterns associated with a forefoot stride and increased cadence reduce impact attenuation following running retraining programs (45,46,119–122,260). Other studies suggest that barefoot running promotes a reduction in delayed or heel strike that may reduce ground reaction force and loading rates in amateur runners (181,217). Therefore, both increased cadence and barefoot running have been hypothesised as clinically valid, field-applicable, and environmentally friendly alternatives to reduce injury risk (102,177,208).

That said, the findings in **SECTION 2** demonstrate two effective technical re-education programs for generating changes in runner biomechanics, aiming to reduce the prevalence of delayed stance, reduce foot angle at initial contact, increase knee and hip angle, following a healthy loading progression for 10-week amateur runners, and without using sophisticated or high-cost technologies, applicable in natural or ecological (non-laboratory) settings.

The 10-week program of increasing basal cadence by 10% showed more conservative changes and taking into consideration that the program is run in the shoes of amateur runners. It can be suggested that it could be of use to runners looking for a more protective and conservative re-education program. In addition, it could allow the use of plantar orthoses as footwear is always worn. Although its effects on pathology have not been studied, so this application should be understood with special caution.

Therefore, these findings are intended to be useful for practical or field (non-laboratory) purposes, e.g., in sport settings for runners, coaches or physical educators, but also in clinical settings for sports physicians, physiotherapists or other clinicians working with amateur runners. Both programs could reduce knee risk factors and increase running efficiency. However, more research is also needed to explore the long-term effects.

Both coaches and clinicians could benefit for practical purposes from retraining sessions with periods of barefoot running as a tool and not an end, with the aim of improving the balance skills of recreational endurance runners, while respecting loading and resting periods in safe surfaces (e.g., soft, flat, and grass or non-slip surface).

5.2. FUTURE PERSPECTIVES

This Doctoral Thesis has evaluated the footstrike pattern, inversion and spatiotemporal variables of a large sample of endurance runners during a long-distance road race, according to gender, at two points (km5 and km15) of a real long-distance race, however, it would be useful to deepen the knowledge of how intra-runner biomechanical and physiological parameters interact by monitoring in shorter periods of time (e.g. each kilometre of the race). A study using wearable wearables during a real competition could provide extensive information on the biomechanical and physiological parameters of the race and the performance of endurance runners.

Similarly, for Section 2 we examined the changes that occurred after 10 weeks of running technique retraining before and after the intervention. The use of wearable sensors could provide knowledge on how runners evolve or modify their running biomechanics, generating weekly or even daily data for each long-distance runner.

Knowledge of shoe biomechanics and biomechanics has shown us that they are related and parameters such as stride type, contact time, stride length, ground reaction forces and kinematics and angular moments can be modified. However, the study of the effect of footwear and the interaction with the two technique re-education programmes proposed were not studied in this Doctoral Thesis, so, with the aim of going deeper into the effects of running re-education and running biomechanics, the classification and description of biomechanical characteristics could be included in future lines of research.

Knowledge of shoe biomechanics and running biomechanics has shown us that they are related and parameters such as footstrike pattern, contact time, step length, ground reaction forces and kinematics and angular moments can be modified. However, the study of the effect of footwear and the interaction with the two technique retraining programs proposed were not studied in this Doctoral Thesis, so, with the aim of going deeper into the effects of running retraining and running biomechanics, the classification and description of biomechanical characteristics could be included in future lines of research.

Evidence from 10 weeks of running retraining programs based on periods of barefoot running and a 10% increase in basal cadence has shown that there are changes shared between the two programs, such as a decrease in foot angle at initial contact, increased knee and hip flexion and greater anterior pelvic tilt in the healthy population. These findings have been suggested by several authors and discussed in this Doctoral Thesis with possible associations to reduce injury risk factors and improve running economy. However, the effects on special populations (e.g. elderly, pregnant or adolescent runners) or injuries (anterior knee pain, patellar tendonitis or Achilles tendonitis) remain unstudied. In addition, the population studied and described were amateur runners, so the effects on elite and high-level runners are also unknown. Therefore, more research would be needed in these population groups to further investigate the effects of barefoot running or the 10% increase in cadence in various population types.

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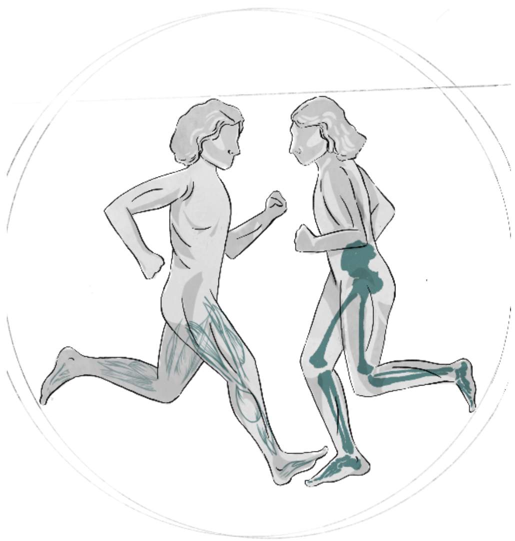

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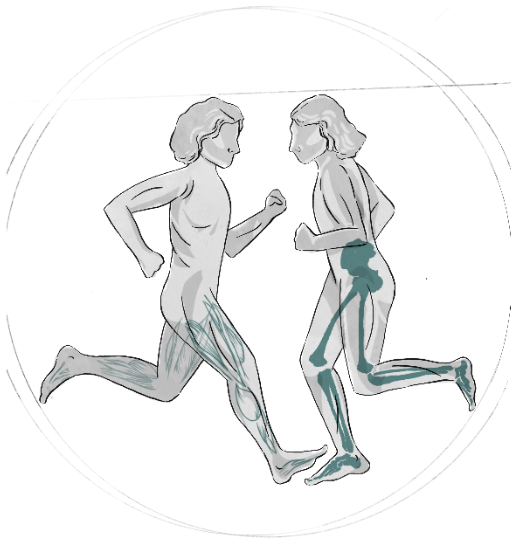
APPENDIX



Original copy of the Certificate of Ethics Committee Approval

UNIVERSIDAD DE GRANADA

Vicerrectorado de Investigación y Transferencia

**COMITE DE ETICA EN INVESTIGACION
DE LA UNIVERSIDAD DE GRANADA**

La Comisión de Ética en Investigación de la Universidad de Granada, visto el informe preceptivo emitido por la Presidenta del Comité en Investigación Humana, tras la valoración colegiada del Comité en sesión plenaria, en el que se hace constar que la investigación propuesta respeta los principios establecidos en la legislación internacional y nacional en el ámbito de la biomedicina, la bioteconología y la bioética, así como los derechos derivados de la protección de datos de carácter personal,

Emite un Informe Favorable en relación a la investigación titulada: 'DESARROLLO DE UN SISTEMA TECNOLÓGICO INTEGRAL PARA LA VALORACIÓN BIOMECÁNICA DE LA TÉCNICA DE CARRERA, SU OPTIMIZACIÓN Y EL DESARROLLO DE PROGRAMAS PARA LA PREVENCIÓN DE LESIONES MUSCULO-ESQUELÉTICAS EN CORREDORES' que dirige D./Dña. ALEJANDRO MOLINA MOLINA, con NIF 45.718.726-Q, quedando registrada con el nº: 788/CEIH/2019.

Granada, a 11 de Marzo de 2019.

EL PRESIDENTE
Fdo: Enrique Herrera Viedma

EL SECRETARIO
Fdo: Fernando Cornet Sánchez del Águila

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Original copy of the Borg scale used in the running protocol and the weekly diary during the running retraining programs.

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Escala de BORG

Versión ESPAÑOLA "ampliada" (adaptada por V.M.Soto)

INSTRUCCIONES:

Durante la sesión presta mucha atención a lo intenso o pesado que usted siente que es el esfuerzo que está realizando. Debe valorar la sensación total del esfuerzo y la fatiga. No considere otros factores como el dolor en las piernas, la falta de respiración o la intensidad de la carga. Intente concentrarse en la sensación total, interna del esfuerzo. No subestime o sobrestime dicha sensación; intente ser tan preciso como le sea posible.

Escala de Esfuerzo Percibido de Borg (Borg RPE)		Pul/min	Grado de intensidad (de 0 a 10)
6	Ningún esfuerzo en absoluto	60-80	0
7	Extremadamente ligero	70-90	1
8		80-100	2
9	Muy ligero	90-110	
10		100-120	3
11	Ligero	110-130	
12		120-140	4
13	Algo pesado-duro	130-150	5
14		140-160	6
15	Pesado-duro	150-170	7
16		160-180	
17	Muy pesado-duro	170-190	8
18		180-200	9
19	Extremadamente pesado-duro	190-210	10
20	Máximo esfuerzo posible	200-220	

Documento elaborado por el HUMAN LAB en el iMUDS (UGR): Human Lab iMUDS Instituto Mixto Universitario Deporte y Salud

Reference, link, quality criteria, journal impact factor and first page of the original copy of the publication of STUDY 1

Latorre-Román PÁ, Soto-Hermoso VM, Garcia-Pinillos F, Gil-Cosano JJ, Robles Fuentes A, Muñoz-Jiménez M, et al. Does Fatigue Affect the Kinematics of Endurance Running? Rev Int Med y Ciencias la Act Física y el Deport. 2021;X(March).

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- JCR (Web of Science): Q4
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ORIGINAL

DOES FATIGUE AFFECT THE KINEMATICS OF ENDURANCE RUNNING?

¿AFECTA LA FATIGA A LA CINEMÁTICA DE LA CARRERA DE RESISTENCIA?

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ABSTRACT

The purpose of this study was to determine the footstrike pattern (FSP), inversion (INV) and spatial-temporal variables in a large sample of recreational runners during a long-distance competition, according to sex and changes in the classification race. A total of 368 men and 67 women, who participated in the XVII International Half Marathon of Cordoba (Spain) were analysed. It was recorded at km 5 and km 15, where high-speed camcorder and 2D-photogrammetric techniques were used to measure FSP, INV, contact time (CT) and flight time (FT). The group that worsened their classification at km 15 increase RFS prevalence

Reference, link, quality criteria, journal impact factor and first page of the original copy of the publication of STUDY 2

Molina-Molina A, Latorre-Román PÁ, Mercado-Palomino E, Delgado-García G, Richards J, Soto-Hermoso VM. The effect of two retraining programs, barefoot running vs increasing cadence, on kinematic parameters: A randomized controlled trial. Scand J Med Sci Sports. 2022 Mar 9;32(3):533–42.

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ORIGINAL ARTICLE

WILEY

The effect of two retraining programs, barefoot running vs increasing cadence, on kinematic parameters: A randomized controlled trial

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The aim of this study was to compare the effects of two 10-week non-laboratory-based running retraining programs on foot kinematics and spatiotemporal parameters in recreational runners. One hundred and three recreational runners (30 ± 7.2 years old, 39% females) were randomly assigned to either: a barefoot retraining group (BAR) with 3 sessions/week over 10 weeks, a cadence retraining group (CAD) who increased cadence by 10% again with 3 sessions/week over 10 weeks and a control group (CON) who did not perform any retraining. The footstrike pattern, footstrike angle (FSA), and spatial-temporal variables at comfortable and high speeds were measured using 2D/3D photogrammetry and a floor-based photocell system. A 3 × 2 ANOVA was used to compare between the groups and 2 time points. The FSA significantly reduced at the comfortable speed by 5.81° for BAR ($p < 0.001$; Cohen's $d = 0.749$) and 4.81° for CAD ($p = 0.002$; Cohen's $d = 0.638$), and at high speed by 6.54° for BAR ($p < 0.001$; Cohen's $d = 0.753$) and by 4.71° for CAD ($p = 0.001$; Cohen's $d = 0.623$). The cadence significantly increased by 2% in the CAD group ($p = 0.015$; Cohen's $d = 0.344$) at comfortable speed and the BAR group showed a 1.7% increase at high speed. BAR and CAD retraining programs showed a moderate effect for reducing FSA and rearfoot prevalence, and a small effect for increasing cadence. Both offer low-cost and feasible tools for gait modification within recreational runners in clinical scenarios.

KEYWORDS
gait retraining, metronome, running form, step rate, unshod

Supplementary Table 1. Spatiotemporal parameters before (pre-test) and after (post-test) a 10-week retraining intervention at comfortable speed.

Variables	Groups	Pre-test Mean (SD)	Post-test Mean (SD)	Mean Difference	P-value (time x group)	Cohen´s d
Foot strike angle (degrees)	BAR	6.85 (7.18)	1.04 (8.30)	-5.815	**0.0001**	0.749
	CAD	7.16 (7.40)	2.31 (7.79)	-4.843	**0.002**	0.638
	CON	4.24 (6.97)	6.05 (6.49)	1.803	0.220	0.269
p-value (group x time)		0.507	0.088			
Contact Time (ms)	BAR	292.61 (21.66)	292.91 (32.34)	0.304	0.940	0.011
	CAD	289.00 (25.34)	286.67 (27.30)	-2.333	0.583	0.088
	CON	289.00 (25.16)	289.14 (25.85)	0.136	0.974	0.005
p-value (group x time)		1.000	1.000			
Flight Time (ms)	BAR	71.50 (24.34)	76.18 (31.64)	4.682	0.250	0.166
	CAD	67.67 (21.96)	68.86 (27.34)	1.19	0.774	0.048
	CON	72.61 (30.70)	77.26 (32.24)	4.652	0.243	0.148
p-value (group x time)		1.000	1.000			
Step length (cm)	BAR	100.70 (9.50)	100.34 (9.03)	-0.362	0.588	0.039
	CAD	98.44 (8.10)	98.54 (8.48)	0.105	0.875	0.013
p-value (group x time)	CON	104.07 (10.41)	105.41 (9.69)	1.346	**0.034**	0.134
		0.151	0.042			
Step frequency (steps/min)	BAR	163.53 (8.45)	164.01 (7.17)	0.474	0.667	0.06
	CAD	167.78 (7.52)	170.51 (8.36)	2.734	**0.015**	0.344
p-value (group x time)	CON	167.5 (7.42)	165.18 (6.82)	-2.322	**0.031**	0.326
		0.228	**0.016**			
Landing Time (ms)	BAR	35.29 (11.73)	28.71 (10.49)	-6.571	**0.001**	0.591
	CAD	35.05 (10.25)	30.23 (10.2)	-4.818	**0.008**	0.472
p-value (group x time)	CON	37.27 (11.72)	39.59 (11.01)	2.318	0.194	0.204
		1.000	**0.004**			
Flat Time (ms)	BAR	114.32 (11.65)	117.05 (14.88)	2.727	0.167	0.204
	CAD	113.62 (11.51)	113.71 (11.15)	0.095	0.962	0.008
p-value (group x time)	CON	113.95 (12.67)	113.77 (15.77)	-0.182	0.926	0.013
		1.000	1.000			
Propulsive Time (ms)	BAR	141.45 (16.78)	142.32 (21.86)	0.864	0.654	0.045
	CAD	138.95 (15.12)	139.5 (16.33)	0.545	0.777	0.035
p-value (group x time)	CON	136.65 (12.21)	134.43 (10.19)	-2.217	0.242	0.197
		0.841	0.357			

Note: Standard deviation (SD); Barefoot group (BAR); Cadence group (CAD); Control group (CON).

Supplementary Table 2. Spatiotemporal parameters before (pre-test) and after (post-test) a 10-week retraining program at high speed

Variables	Groups	Pre-test Mean (SD)	Post-test Mean (SD)	Mean Difference	P-value (time x group)	Cohen´s d
Foot strike angle (degrees)	BAR	8.93 (7.68)	2.39 (9.57)	-6.542	**0.0001**	0.753
	CAD	9.72 (6.93)	5.02 (8.11)	-4.705	**0.001**	0.623
	CON	5.30 (8.20)	8.00 (7.64)	2.703	**0.047**	0.340
p-value (group x time)		0.169	0.095			
Contact Time (ms)	BAR	235.87 (26.56)	236.74 (33.7)	0.87	0.745	0.029
	CAD	231.95 (22)	225.77 (25.12)	-6.182	**0.027**	0.262
	CON	225.9 (20.87)	226 (20.02)	0.1	0.972	0.005
p-value (group x time)		0.506	0.544			
Flight Time (ms)	BAR	106.74 (28.38)	104.57 (29.87)	-2.174	0.491	0.074
	CAD	97.76 (17.63)	97.1 (20.45)	-0.667	0.840	0.035
	CON	104.77 (24.36)	111.5 (26.38)	6.727	**0.04**	0.265
p-value (group x time)		0.662	0.223			
Step length (cm)	BAR	132.8 (18.92)	130.82 (18.86)	-1.983	**0.030**	0.105
	CAD	127.62 (12.92)	126.72 (13.5)	-0.905	0.335	0.068
	CON	138.44 (11.98)	141.42 (11.72)	2.978	**0.001**	0.251
p-value (group x time)		0.059	**0.006**			
Step frequency (steps/min)	BAR	174.89 (9.29)	177.77 (8.9)	2.877	**0.031**	0.316
	CAD	182.06 (10.26)	184.08 (11.83)	2.019	0.118	0.182
	CON	183.96 (9.58)	179.3 (7.77)	-4.660	**0.001**	0.534
p-value (group x time)		**0.009**	0.098			
Landing Time (ms)	BAR	27.86 (7.98)	24.24 (9.51)	-3.619	**0.017**	0.412
	CAD	27.74 (8.99)	26.87 (10.53)	-0.87	0.540	0.089
	CON	28.19 (10.33)	30.14 (8.81)	1.952	0.191	0.203
p-value (group x time)		1.000	0.157			
Flat Time (ms)	BAR	91 (14.83)	91.61 (17.09)	0.609	0.656	0.038
	CAD	93.05 (7.39)	91.33 (8.19)	-1.714	0.234	0.221
	CON	87.85 (11.21)	88.05 (11.64)	0.2	0.892	0.018
p-value (group x time)		0.478	1.000			
Propulsive Time (ms)	BAR	111.95 (14.64)	116.86 (17.56)	4.909	**0.004**	0.304
	CAD	110.91 (12.94)	108.41 (12.42)	-2.5	0.138	0.197
	CON	108.64 (7.49)	106.5 (7.79)	-2.136	0.204	0.280
p-value (group x time)		1.000	**0.035**			

Note: Standard deviation (SD); Barefoot group (BAR); Cadence group (CAD); Control group (CON).

Supplementary Table 3. Variability of the spatiotemporal parameters and foot strike angle before (pre-test) and after (post-test) a 10-week retraining program at comfortable speed.

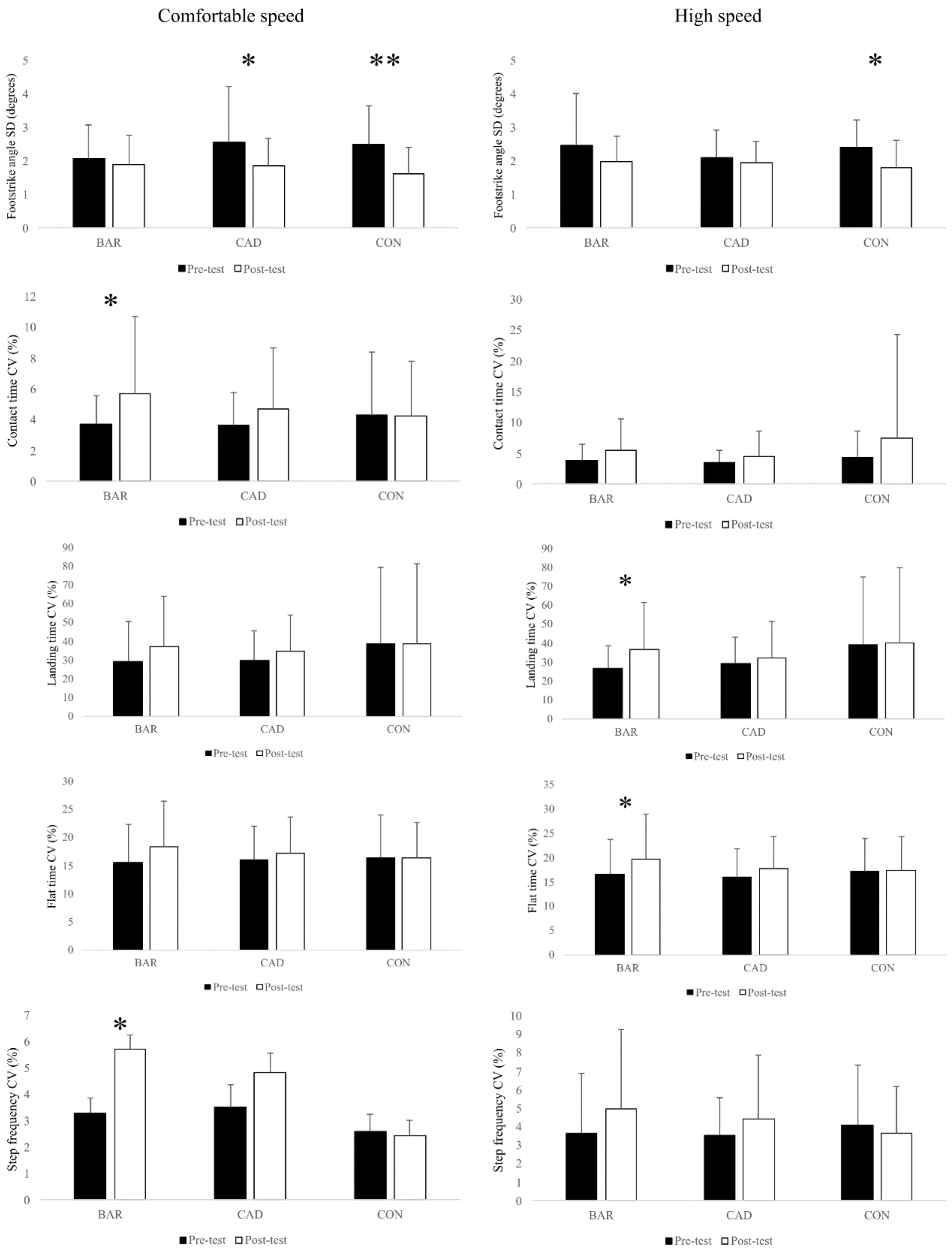
Variables	Groups	Pre-test Mean (SD)	Post-test Mean (SD)	Mean Difference	P-value (time x group)	Cohen´s d
Foot strike angle SD (degrees)	BAR	2.06 (1.00)	1.89 (0.88)	-0.168	0.541	0.178
	CAD	2.57 (1.64)	1.85 (0.83)	-0.726	**0.010**	0.560
	CON	2.50 (1.16)	1.61 (0.78)	-0.888	**0.001**	0.950
		0.353	0.410			
p-value (group x time)						
Contact Time CV (%)	BAR	3.74 (1.83)	5.67 (5.06)	1.926	**0.027**	0.506
	CAD	3.63 (2.15)	4.72 (3.97)	1.091	0.213	0.341
	CON	4.3 (4.13)	4.23 (3.59)	-0.071	0.932	0.018
p-value (group x time)		1.000	0.749			
Flight Time CV (%)	BAR	17.23 (10.69)	23.92 (15.81)	6.683	0.074	0.495
	CAD	19.91 (9.6)	23.44 (14.19)	3.527	0.352	0.291
	CON	21.73 (27.7)	16.65 (8.22)	-5.079	0.164	0.249
p-value (group x time)		1.000	0.184			
Step length CV (%)	BAR	2.66 (0.57)	2.57 (0.54)	-0.091	0.362	0.164
	CAD	2.64 (0.84)	2.71 (0.75)	0.073	0.477	0.091
p-value (group x time)	CON	2.6 (0.64)	2.44 (0.57)	-0.163	0.100	0.268
		1.000	0.414			
Step frequency CV (%)	BAR	3.3 (1.72)	5.7 (6.33)	2.400	**0.014**	0.518
	CAD	3.51 (2.09)	4.81 (3.64)	1.3	0.188	0.438
p-value (group x time)	CON	4.18 (3.45)	4.01 (3.37)	-0.171	0.856	0.050
		0.715	0.654			
Landing Time (ms)	BAR	29.34 (21.1)	37.24 (26.79)	7.904	0.112	0.328
	CAD	29.78 (15.48)	34.37 (19.6)	4.586	0.364	0.260
	CON	38.41 (40.84)	38.45 (42.94)	0.037	0.994	0.001
p-value (group x time)		0.833	1.000			
Flat Time (ms)	BAR	15.5 (6.84)	18.3 (8.16)	2.800	**0.027**	0.372
	CAD	16.03 (5.93)	17.21 (6.46)	1.177	0.356	0.190
	CON	16.38 (7.51)	16.34 (6.33)	-0.033	0.978	0.005
p-value (group x time)		1.000	1.000			
Propulsive Time (ms)	BAR	8.98 (2.43)	10.15 (3.59)	1.174	0.058	0.383
	CAD	8.8 (2.78)	9.08 (2.6)	0.282	0.652	0.105
	CON	8.57 (2.71)	8.16 (2.05)	-0.408	0.495	0.170
p-value (group x time)		1.000	0.054			

Note: Standard deviation (SD); Barefoot group (BAR); Cadence group (CAD); Control group (CON).

Supplementary Table 4. Variability of the spatiotemporal parameters and foot strike angle before (pre-test) and after (post-test) a 10-week retraining program at high speed

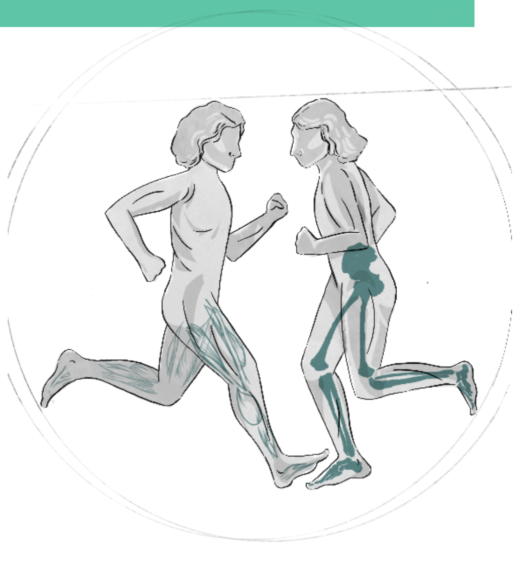
Variables	Groups	Pre-test Mean (SD)	Post-test Mean (SD)	Mean Difference	P-value (time x group)	Cohen´s d
Foot strike angle (degrees)	BAR	2.45 (1.55)	1.97 (0.76)	-0.476	0.072	0.390
	CAD	2.10 (0.83)	1.96 (0.62)	-0.137	0.601	0.187
	CON	2.41 (0.82)	1.79 (0.82)	-0.624	**0.017**	0.757
p-value (group x time)		0.534	0.453			
Contact Time (ms)	BAR	3.9 (2.57)	5.57 (5.01)	1.665	0.449	0.418
	CAD	3.51 (1.95)	4.47 (4.1)	0.955	0.671	0.297
	CON	4.4 (4.3)	7.48 (16.78)	3.079	0.155	0.251
p-value (group x time)		1.000	1.000			
Flight Time (ms)	BAR	11.71 (9.32)	13.82 (9.52)	2.104	0.081	0.223
	CAD	10.05 (3.88)	11.69 (4.52)	1.641	0.182	0.389
	CON	10.24 (3.95)	9.51 (4.1)	-0.725	0.536	0.180
p-value (group x time)		1.000	0.081			
Step length (cm)	BAR	2.41 (0.93)	2.57 (0.69)	0.152	0.349	0.185
	CAD	2.50 (0.97)	2.40 (0.51)	0.105	0.528	0.135
p-value (group x time)	CON	2.24 (0.64)	2.16 (0.61)	0.079	0.618	0.123
		0.902	0.550			
Step frequency (steps/min)	BAR	3.67 (3.2)	4.96 (4.28)	1.296	0.074	0.343
	CAD	3.53 (2.03)	4.43 (3.48)	0.895	0.223	0.314
p-value (group x time)	CON	4.08 (3.25)	3.65 (2.53)	-0.433	0.537	0.149
		1.000	0.604			
Landing Time (ms)	BAR	26.59 (12.2)	36.46 (25.12)	9.870	**0.016**	0.500
	CAD	29.04 (13.92)	31.94 (19.62)	2.9	0.481	0.170
	CON	39.31 (35.51)	40.1 (39.7)	0.783	0.842	0.021
p-value (group x time)		0.203	1.000			
Flat Time (ms)	BAR	16.63 (7)	19.57 (9.32)	2.935	**0.013**	0.356
	CAD	15.94 (5.87)	17.73 (6.58)	1.786	0.134	0.287
	CON	17.21 (6.6)	17.22 (7.12)	0.004	0.997	0.001
p-value (group x time)		1.000	0.910			
Propulsive Time (ms)	BAR	10.29 (3.81)	11.21 (3.66)	0.926	0.096	0.248
	CAD	9.18 (2.63)	10.05 (2.54)	0.873	0.124	0.338
	CON	9.07 (2.51)	8.58 (2.12)	-0.492	0.363	0.212
p-value (group x time)		0.520	**0.007**			

Note: Standard deviation (SD); Barefoot group (BAR); Cadence group (CAD); Control group (CON).



Supplementary Figure 1. Variability of the spatiotemporal parameters and foot strike angle before (pre-test) and after (post-test) a 10-week retraining program at comfortable speed (left column) and high speed (right column) for pre- test and post- test for each group. *denotes p < 0.05; **denotes p < 0.01; ***denotes p < 0.001.

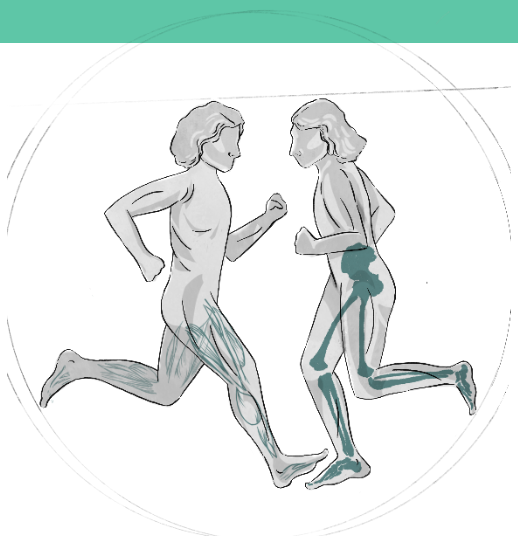
KNOWLEDGE OF BIOMECHANICS AND TRAINING TECHNOLOGIES



Knowledge of biomechanics and training technologies

	Manufacturer
Baropodometric platform, RS Scan	RS Scan (United Kingdom)
Baropodometric platforms, SensorMedica	Sensor Medica (Italy)
Baropodometric insoles, TekScan	TekScan (USA)
3D photogrammetric system, Optitrack	Optitrack (USA)
3D photogrammetric system, SIMI Motion	Simi Motion Systems (Germany)
Markerless 3D photogrammetric system, SIMI Shape	Simi Motion Systems (Germany)
3D photogrammetric system, Qualisys	Qualisys Mocap Systems (Sweden)
2D photogrammetric system, SIMI Aktisys	Simi Motion Systems (Germany)
3D photogrammetric system TRIO	Optitrack (USA)
Biomechanical analysis software, Visual3D	CMotion (USA)
Biomechanical analysis software, VideoSpeed	Universidad de Granada (Spain)
Biomechanical analysis software, Kwon3D	Kwon3D (South Korea)
Heart rate monitors	Garmin, Polar and First Beat
Electromyography 4 channels mDurance	Mdurance Solution (Spain)
Electromyography 16 channels Trigno	Delsys (USA)
Video cameras	GoPro, Samnsung, Casio.
Force Platform, Kistler	Kistler (USA)
Photocell system, Optogait	Microgait (Italy)
Photocell system, Witty	Microgait (Italy)
Statistical software, SPSS	IBM (USA)
MATLAB software	MathWorks
Linear encoder, SmartCoach	SmartCoach™ (Sweden)

CURRICULUM VITAE



CURRÍCULUM VÍTAE NORMALIZADO

ALEJANDRO MOLINA MOLINA

Generado desde: Pruebas de SICA (Central)

Fecha del documento: 21/12/2022

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Resumen libre del currículum

Descripción breve de la trayectoria científica, los principales logros científico-técnicos obtenidos, los intereses y objetivos científico-técnicos a medio/largo plazo de la línea de investigación. Incluye también otros aspectos o peculiaridades importantes.

Principal línea de investigación está orientada a la Biomecánica Deportiva y al Desarrollo Tecnológico para el Análisis del Movimiento. Tesis doctoral centrada en el campo de la Biomecánica de la Carrera/Running y el Reentrenamiento del Running mediante metodologías de Biofeedback o Ecológicas (como carrera descalzo). En los últimos años, ha ampliado líneas de investigación en el campo de la Electromiografía de Superficie, Análisis del Rendimiento-Optimización y Prevención de Riesgos Musculoesqueléticos aplicados al Deporte (voleibol y fútbol principalmente), y Exoesqueletos para favorecer la marcha en población militar.

ALEJANDRO MOLINA MOLINA

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Teléfono móvil: **6XXXXX**

Situación profesional actual

Entidad empleadora: Universidad de San Jorge
Departamento: Escuela de Arquitectura y Tecnología
Categoría profesional: Docente
Ciudad entidad empleadora: Zaragoza, Aragón, España
Teléfono: 625538520
Fecha de inicio: 15/12/2020
Régimen de dedicación: Tiempo completo

Entidad empleadora: Universidad de Granada. Facultad de Ciencias de la Actividad Física y del Deporte
Categoría profesional: Investigador colaborador
Ciudad entidad empleadora: Instituto Mixto Universitario Deporte y Salud (IMUDS),
Fecha de inicio: 22/12/2017

Cargos y actividades desempeñados con anterioridad

	Entidad empleadora	Categoría profesional	Fecha de inicio
		Jefe de Salud (I+D+i) y Biomecánico en mDurance Solutions S.L.	01/11/2017

Ciudad entidad empleadora: Granada,
Categoría profesional: Jefe de Salud (I+D+i) y Biomecánico en mDurance Solutions S.L.
Fecha de inicio: 01/11/2017 **Duración:** 729 días

Formación académica recibida

Titulación universitaria

Estudios de 1º y 2º ciclo, y antiguos ciclos (Licenciados, Diplomados, Ingenieros Superiores, Ingenieros Técnicos, Arquitectos)

Titulación universitaria: Otros
Nombre del título: Licenciatura en Ciencias de la Actividad Física y de Deporte
Entidad de titulación: Universidad de Granada
Fecha de titulación: 2012

Otra formación universitaria de posgrado

Tipo de formación: Máster
Titulación de posgrado: Máster Universitario en Investigación en Actividad Física y Deporte
Entidad de titulación: Universidad de Granada
Fecha de titulación: 2014

Formación especializada, continuada, técnica, profesionalizada, de reciclaje y actualización (distinta a la formación académica reglada y a la sanitaria)

1 **Tipo de la formación:** Curso
Título de la formación: Jornadas Internacionales de Investigación en Ciencias de la Actividad Física y el Deporte
Entidad de titulación: Universidad de Jaen
Fecha de finalización: 27/11/2020

2 **Tipo de la formación:** Curso
Título de la formación: Efectos de la fuerza muscular en la salud, rehabilitación y rendimiento deportivo
Entidad de titulación: Universidad de Las Américas - Quito. Facultad de Derecho
Fecha de finalización: 25/09/2020

3 **Tipo de la formación:** Curso
Título de la formación: Motor Control Days mDurance
Entidad de titulación: mDurance S.L.
Fecha de finalización: 03/04/2020

4 **Tipo de la formación:** Curso
Título de la formación: Programación en Matlab
Entidad de titulación: Universidad de Granada.
Fecha de finalización: 22/03/2019

5 **Tipo de la formación:** Curso
Título de la formación: Curso de Macros en Excel
Entidad de titulación: Universidad de Granada
Fecha de finalización: 27/09/2017

6 **Tipo de la formación:** Curso
Título de la formación: The synchronised use between Qualisys Motion Capture System and force platforms and surface electromyography
Entidad de titulación: Qualisys Motion Capture
Fecha de finalización: 20/05/2017

7 **Tipo de la formación:** Curso
Título de la formación: NSCA, Certified Personal Trainer
Entidad de titulación: NCSA Spain
Fecha de finalización: 07/03/2017

8 **Tipo de la formación:** Curso
Título de la formación: Curso de Inmersión lingüística
Entidad de titulación: Universidad Internacional Menéndez Pelayo
Fecha de finalización: 20/11/2015

9 **Tipo de la formación:** Curso
Título de la formación: IV PGA SEMINARIO PGA SOBRE BIOMECANICA Y TÉCNICA DEL GOLF
Entidad de titulación: Professional Golf Tours
Fecha de finalización: 27/10/2015

10 **Tipo de la formación:** Curso
Título de la formación: SIMI Educations Days 2015 (Sistema Captura 3D con marcadores y markerless)
Entidad de titulación: SIMI Reallity Motion Systems
Fecha de finalización: 22/10/2015

11 **Tipo de la formación:** Curso
Título de la formación: OPTITRACK y MOTIVE Optical Motion Capture Software
Entidad de titulación: INGEVIDEO S.A.
Fecha de finalización: 06/05/2015

12 **Tipo de la formación:** Curso
Título de la formación: Entrenador Nacional de Atletismo
Entidad de titulación: Real Federación Española de Atletismo
Fecha de finalización: 21/04/2015

13 **Tipo de la formación:** Curso
Título de la formación: Biomecanica de la Marcha, Carrera y Postura
Entidad de titulación: iBiomechanics S.L.
Fecha de finalización: 20/02/2015

14 **Tipo de la formación:** Curso
Título de la formación: Voluntariado de Biomecánico Deportivo en Servicio Médico
Entidad de titulación: XXVII Universiada de Invierno 2015
Fecha de finalización: 14/02/2015

15 **Tipo de la formación:** Curso
Título de la formación: Visual3D software (C-Motion) and Qualisys Motion Capture System
Fecha de finalización: 26/06/2014

16 **Tipo de la formación:** Curso
Título de la formación: Formación de GAITRite y KWON3D
Fecha de finalización: 30/04/2014

17 **Tipo de la formación:** Curso
Título de la formación: Formación en Plataformas Baropodométricas (SensorMedica) y diseño 3D de plantillas
Entidad de titulación: Sensor Medica
Fecha de finalización: 01/02/2014

Actividad docente

Formación académica impartida

1 **Nombre de la asignatura/curso:** Anatomía Aplicada al Movimiento Humano
Tipo de docencia: Teórica presencial
Tipo de asignatura: Troncal
Curso que se imparte: 2
Fecha de finalización: 01/09/2021
Entidad de realización: Universidad de San Jorge. Escuela de Arquitectura y Tecnología
Tipo de entidad: Centros y Estructuras Universitarios y Asimilados

2 **Nombre de la asignatura/curso:** Bases Documentales y de la Información
Tipo de docencia: Teórica presencial
Tipo de asignatura: Troncal
Curso que se imparte: 1
Fecha de finalización: 01/09/2021
Entidad de realización: Universidad San Jorge

3 **Nombre de la asignatura/curso:** Biomecánica Deportiva
Tipo de docencia: Teórica presencial
Tipo de asignatura: Troncal
Curso que se imparte: 4
Fecha de finalización: 01/09/2021
Entidad de realización: Universidad San Jorge

4 **Nombre de la asignatura/curso:** Fundamentos de la Biomecánica
Tipo de docencia: Teórica presencial
Tipo de asignatura: Troncal
Curso que se imparte: 2
Fecha de finalización: 01/09/2021
Entidad de realización: Universidad San Jorge

5 **Nombre de la asignatura/curso:** Biomecánica Humana
Tipo de docencia: Teórica presencial
Tipo de asignatura: Obligatoria
Curso que se imparte: Primero
Fecha de finalización: 15/12/2020
Entidad de realización: Universidad de San Jorge **Tipo de entidad:** Universidad

6 **Nombre de la asignatura/curso:** Fisioterapia Deportiva
Tipo de docencia: Prácticas de Laboratorio
Tipo de asignatura: Obligatoria
Curso que se imparte: Cuarto
Fecha de finalización: 15/12/2020
Entidad de realización: Universidad de San Jorge **Tipo de entidad:** Universidad

7 **Nombre de la asignatura/curso:** Electromiografía de superficie aplicada en fisioterapia
Tipo de docencia: Teórica presencial
Curso que se imparte: Cuarto
Fecha de finalización: 14/03/2019
Entidad de realización: Faculta de Ciencias de la Salud

8 **Nombre de la asignatura/curso:** Uso de tecnologías aplicadas a la biomecánica deportiva
Curso que se imparte: III Edición Máster Propio de Optimización del Entrenamiento y Readaptación Físcio-Deportiva
Fecha de finalización: 02/12/2017
Entidad de realización: Fundación Universitaria San Pablo Ceu **Tipo de entidad:** Fundación

9 **Nombre de la asignatura/curso:** Curso Atención Integral al Corredor
Fecha de finalización: 27/10/2017
Entidad de realización: iBiomechanics

10 **Nombre de la asignatura/curso:** Uso de tecnologías aplicadas a la biomecánica deportiva
Tipo de docencia: Prácticas de Laboratorio
Curso que se imparte: II Edición del Master Propio Optimizacion del Entrenamiento y Readaptación Fisico-Deportiva
Fecha de finalización: 26/11/2016
Entidad de realización: Fundación Universitaria San Pablo Ceu **Tipo de entidad:** Fundación

11 **Nombre de la asignatura/curso:** Curso Atención Integral al Corredor
Fecha de finalización: 11/11/2016
Entidad de realización: iBiomechanics

12 **Nombre de la asignatura/curso:** Curso OPTOGAIT, GYKO, RE-POWER
Fecha de finalización: 18/12/2015
Entidad de realización: iBiomechanics

13 **Nombre de la asignatura/curso:** Curso Atención Integral al Corredor
Fecha de finalización: 23/10/2015

14 **Nombre de la asignatura/curso:** Curso Atención Integral al Corredor
Fecha de finalización: 18/09/2015
Entidad de realización: iBiomechanics

15 **Nombre de la asignatura/curso:** Curso Atención Integral al Corredor
Fecha de finalización: 23/04/2015
Entidad de realización: iBiomechanics

Experiencia científica y tecnológica

Actividad científica o tecnológica

Proyectos de I+D+i financiados en convocatorias competitivas de Administraciones o entidades públicas y privadas

1 **Nombre del proyecto:** Análisis de la Prevalencia de Altas Capacidades y Talento en Niños de 6 a 12 años de la Provincia de Jaén y su Relación con Variables Sociodemográficas
Ámbito geográfico: Autonómica
Grado de contribución: Investigador/a
Entidad de realización: INSTITUTO DE ESTUDIOS GIENNENSES (DIPUTACION PROVINCIAL DE JAEN)
Nombres investigadores principales (IP, Co-IP,...): PEDRO ANGEL LATORRE ROMAN
Nº de investigadores/as: 16
Cód. según financiadora: IEG_2017_2017/00505/001
Fecha de inicio: 10/11/2017 **Duración:** 343 días
Cuantía total: 3,500 €

2 **Nombre del proyecto:** MONITORIZACION Y FOMENTO DE HABITOS SALUDABLES, MEDIANTE UNA PLATAFORMA BASADA EN SENSORES PORTABLES Y ASESORES VIRTUALES, PARA LA PROMOCION DEL ENVEJECIMIENTO ACTIVO EN POBL
Ámbito geográfico: Nacional
Entidad de realización: Ministerio De Economía Y Competitividad
Nombres investigadores principales (IP, Co-IP,...): VICTOR MANUEL SOTO HERMOSO; MANUEL NOGUERA GARCÍA
Nº de investigadores/as: 13
Cód. según financiadora: DEP2015-70980-R
Fecha de inicio: 01/01/2016 **Duración:** 1095 días
Cuantía total: 102,850 €

3 **Nombre del proyecto:** Informatización de Máquina Patentada para la Medición de Propiedades Viscoelásticas del Tríceps Sural
Grado de contribución: Investigador/a
Entidad de realización: Universidad de Granada
Nombres investigadores principales (IP, Co-IP,...): FEDERICO PARIS GARCIA
Nº de investigadores/as: 10
Cód. según financiadora: V14-2015
Fecha de inicio: 28/05/2015 **Duración:** 217 días

4 **Nombre del proyecto:** Informatización de Máquina Patentada para la Medición de Propiedades Viscoelásticas del Tríceps Sural
Ámbito geográfico: Autonómica
Grado de contribución: Investigador/a
Entidad de realización: UNIVERSIDAD DE GRANADA
Nombres investigadores principales (IP, Co-IP,...): MANUEL NOGUERA GARCÍA; FEDERICO PARIS GARCIA
Nº de investigadores/as: 11
Cód. según financiadora: CEI2015-MP-V14
Fecha de inicio: 01/01/2015 **Duración:** 364 días
Cuantía total: 2,000 €

5 **Nombre del proyecto:** Efecto de la carga de la mochila sobre los parámetros de locomoción en escolares de primaria
Ámbito geográfico: Autonómica
Grado de contribución: Investigador/a
Entidad de realización: UNIVERSIDAD DE GRANADA
Nombres investigadores principales (IP, Co-IP,...): JOSE MARIA HEREDIA JIMENEZ
Nº de investigadores/as: 8
Cód. según financiadora: CEI2014-MPBS18
Fecha de inicio: 28/05/2014 **Duración:** 217 días
Cuantía total: 3,000 €

6 **Nombre del proyecto:** SISTEMA ERGONOMICO INTEGRAL PARA LA EVALUACION DE LA LOCOMOCION COMO PREDICTOR DE LA CALIDAD DE VIDA RELACIONADA CON LA SALUD EN MAYORES
Ámbito geográfico: Nacional
Grado de contribución: Investigador/a
Entidad de realización: MINISTERIO DE CIENCIA E INNOVACIÓN
Nombres investigadores principales (IP, Co-IP,...): VICTOR MANUEL SOTO HERMOSO
Nº de investigadores/as: 15
Cód. según financiadora: DEP2012-40069
Fecha de inicio: 01/01/2013 **Duración:** 1275 días
Cuantía total: 49,140 €

Actividades científicas y tecnológicas

Producción científica

Publicaciones, documentos científicos y técnicos

1 ALEJANDRO MOLINA MOLINA; PEDRO ANGEL LATORRE ROMAN; Elia Mercado-Palomino; Gabriel Delgado García; VICTOR MANUEL SOTO HERMOSO. The effect of two retraining programs, barefoot running vs increasing cadence, on kinematic parameters: A randomized controlled trial. Scandinavian Journal of Medicine & Science in Sports. May, pp. 1 - 10. 2022. ISSN 1600-0838
Tipo de producción: Artículo científico

2 Alberto Filter Ruger; Jesús Olivares Jabalera; ALEJANDRO MOLINA MOLINA; Jaime Morente Sánchez; JOSÉ ROBLES RODRÍGUEZ; ALFREDO SANTALLA HERNÁNDEZ; BERNARDO REQUENA. Reliability and Usefulness of Maximum Soccer-Specific Jump Test: a Valid and Cost-effective System to Measure on Soccer Field. Sports Biomechanics. 2022. ISSN 1476-3141
Tipo de producción: Artículo científico

3 Jesús Vera Vilchez; Beatriz Redondo Cabrera; Ortega-sánchez, Alba; ALEJANDRO MOLINA MOLINA; Rubén Molina Romero; Rosenfield, Mark; RAIMUNDO JIMÉNEZ RODRÍGUEZ. Blue-blocking filters do not alleviate signs and symptoms of digital eye strain. Clinical & Experimental Optometry. 2022. ISSN 0816-4622
Tipo de producción: Artículo científico

4 Jaén-carrillo, Diego; Roche-seruendo, Luis Enrique; ALEJANDRO MOLINA MOLINA; Cardiel-sánchez, Silvia; Cartón-llorente, Antonio; García-Pinillos, Felipe. Influence of the Shod Condition on Running Power Output: An Analysis in Recreationally Active Endurance Runners. Sensors. 22 - 13, pp. 4828 - 4828. 2022. ISSN 1424-3210
Tipo de producción: Artículo científico

5 Pablo Molina García; ALEJANDRO MOLINA MOLINA; Smeets, Annemie; Migueles, Jairo H.; Francisco B. Ortega Porcel; Vanrenterghem, Jos. Effects of integrative neuromuscular training on the gait biomechanics of children with overweight and obesity. Scandinavian Journal of Medicine & Science in Sports. pp. 1119-1130 - 1130. 2022. ISSN 1600-0838
Tipo de producción: Artículo científico

6 Santiago Alejo Ruiz Alias; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO; FELIPE GARCÍA PINILLOS. A systematic review of the effect of running shoes on running economy, performance and biomechanics: analysis by brand and model. Sports Biomechanics. pp. 1 - 22. 2022. ISSN 1476-3141
Tipo de producción: Artículo científico

7 Alberto Filter Ruger; Jesús Olivares Jabalera; ALEJANDRO MOLINA MOLINA; JOSÉ ROBLES RODRÍGUEZ; BERNARDO REQUENA; ALFREDO SANTALLA HERNÁNDEZ. Effect of Ball Inclusion on Jump Performance in Soccer Players: A Biomechanical Approach. 2021. ISSN 2473-3938
Tipo de producción: Artículo científico

8 PEDRO ANGEL LATORRE ROMAN; VICTOR MANUEL SOTO HERMOSO; FELIPE GARCÍA PINILLOS; José Juan Gil Cosano; ALEJANDRO ROBLES FUENTES; MARCOS MUÑOZ JIMENEZ; ALEJANDRO MOLINA MOLINA. Does Fatigue Affect the Kinematics of Endurance Running?. Revista Internacional de Medicina y Ciencias de la Actividad Física y del Deporte. In press, 2021. ISSN 1577-0354
Tipo de producción: Artículo científico

9 Pablo Molina García; Miranda-aparicio, Damian; ALEJANDRO MOLINA MOLINA; Abel Plaza Florido; Jairo Hidalgo Migueles; José Rafael Mora González; Cristina Cadenas Sánchez; Irene Esteban-Cornejo; Maria Rodriguez García; Solis-urra, Patricio; Vanrenterghem , Jos; Francisco B. Ortega Porcel. Effects of Exercise on Plantar Pressure during Walking in Children with Overweight/Obesity.Medicine & Science in Sports & Exercise. 52 - 3, pp. 654 - 662. 2020. ISSN 0195-9131

Tipo de producción: Artículo científico

Fuente de impacto: WOS (JCR)
Índice de impacto: 4.029

10 Fábrica, Carlos Gabriel; Ferraro, Damian; Elia Mercado-Palomino; ALEJANDRO MOLINA MOLINA; IGNACIO CHIROSA RIOS. Differences in Utilization of Lower Limb Muscle Power in Squat Jump With Positive and Negative Load. Frontiers in Physiology. 11 - Junio, pp. 1 - 8. 2020. ISSN 1664-042X

Tipo de producción: Artículo científico

Fuente de impacto: WOS (JCR)
Índice de impacto: 3.367

11 Elia Mercado-Palomino; Richards, Jim; ALEJANDRO MOLINA MOLINA; JOSE MANUEL BENITEZ SANCHEZ; AURELIO UREÑA ESPA. Can kinematic and kinetic differences between planned and unplanned volleyball block jump-landings be associated with injury risk factors?. Gait & Posture. 79 - April, pp. 71 - 79. 2020. ISSN 0966-6362

Tipo de producción: Artículo científico

Fuente de impacto: WOS (JCR)
Índice de impacto: 2.349

12 ALEJANDRO MOLINA MOLINA; Emilio José Ruiz Malagón; Francisco Carrillo Pérez; Luis Enrique Roche Seruendo Seruendo; Miguel Damas Hermoso; Oresti Baños Legrán; FELIPE GARCÍA PINILLOS. Validation of mDurance, A Wearable Surface Electromyography System for Muscle Activity Assessment. Frontiers in Physiology. 11 - November, 2020. ISSN 1664-042X

Tipo de producción: Artículo científico

Fuente de impacto: WOS (JCR)
Índice de impacto: 3.367

13 FELIPE GARCÍA PINILLOS; ALEJANDRO MOLINA MOLINA; JUAN ANTONIO PÁRRAGA MONTILLA; PEDRO ANGEL LATORRE ROMAN. Kinematic alterations after two high-intensity intermittent training protocols in endurance runners. Journal of Sport and Health Science. 8 - 5, pp. 442 - 449. 2019. Disponible en Internet en: <http://http://www.sciencedirect.com/science/article/pii/S2095254616301004>. ISSN 2095-2546

Tipo de producción: Artículo científico

Fuente de impacto: WOS (JCR)
Índice de impacto: 5.2

14 Gabriel Delgado García; Vanrenterghem, Jos; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO. Does stroke performance in amateur tennis players depend on functional power generating capacity?. Journal of Sports Medicine and Physical Fitness. 59 - 5, pp. 760 - 766. 2018. ISSN 1827-1928

Tipo de producción: Artículo científico

Fuente de impacto: WOS (JCR)
Índice de impacto: 1.302

15 Pablo Molina García; Jairo Hidalgo Migueles; Cristina Cadenas Sánchez; Irene Esteban-Cornejo; José Rafael Mora González; Abel Plaza Florido; ALEJANDRO MOLINA MOLINA; Gabriel Delgado García; Francisco B. Ortega Porcel. Fatness and fitness in relation to functional movement quality in overweight and obese children. Journal of Sports Sciences. 2018. ISSN 1466-447X
Tipo de producción: Artículo científico
Fuente de impacto: WOS (JCR)
Índice de impacto: 2.811

16 FELIPE GARCÍA PINILLOS; ALEJANDRO MOLINA MOLINA; PEDRO ANGEL LATORRE ROMAN. Impact of an incremental running test on jumping kinematics in endurance runners: can jumping kinematic explain the post-activation potentiation phenomenon?. 15 - 2, pp. 103 - 112. 2016.
Tipo de producción: Artículo científico

17 ALBERTO RUIZ ARIZA; FELIPE GARCÍA PINILLOS; ALEJANDRO MOLINA MOLINA; PEDRO ANGEL LATORRE ROMAN. Influence of competition on vertical jump, kicking speed, sprint and agility of young football players. 37 - 2, pp. 109 - 118. 2015.
Tipo de producción: Artículo científico

18 PEDRO ANGEL LATORRE ROMAN; MARCOS MUÑOZ JIMENEZ; VICTOR MANUEL SOTO HERMOSO; ALEJANDRO MOLINA MOLINA; ALEJANDRO ROBLES FUENTES; FELIPE GARCÍA PINILLOS. Acute effect of a long-distance road competition on foot strike patterns, inversion and kinematics parameters in endurance runners. International Journal of Performance Analysis in Sport. 15, pp. 588 - 597. 2015. ISSN 2474-8668
Tipo de producción: Artículo científico
Fuente de impacto: WOS (JCR)
Índice de impacto: 1,014

Trabajos presentados en congresos nacionales o internacionales

1 **Título del trabajo:** Fiabilidad de la aplicación MyMocap para el cálculo de variables angulares de tronco, pelvis y rodilla en el plano frontal
Nombre del congreso: I Congreso Internacional y III Congreso Nacional de Rendimiento Deportivo, Actividad Física y Salud y Experiencias Educativas en Educación Física
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: Jaén,
Fecha de celebración: 23/04/2021
Jesús Olivares Jabalera; Ismael Navarro Marchal; ALEJANDRO MOLINA MOLINA; FELIPE GARCÍA PINILLOS; VICTOR MANUEL SOTO HERMOSO.

2 **Título del trabajo:** La presencia del balón en el salto en fútbol: análisis biomecánico
Nombre del congreso: XLII CONGRESO DE LA SOCIEDAD IBÉRICA DE BIOMECÁNICA Y BIOMATERIALES
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Facultad de Ciencias de la Actividad Física y del Deporte INEF UNIVERSIDAD POLITECNICA DE MADRID,
Fecha de celebración: 15/11/2019
Jesús Olivares Jabalera; ALEJANDRO MOLINA MOLINA; Fílter, Alberto; VICTOR MANUEL SOTO HERMOSO; BERNARDO REQUENA.

3 **Título del trabajo:** Effect of two different retraining programs on popular long-distance runners in terms of postural balance
Nombre del congreso: 24th annual congress of the European College of Sport Science

Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: PRAGUE. CZECH REPUBLIC,
Fecha de celebración: 03/07/2019
ALEJANDRO MOLINA MOLINA; Elia Mercado-Palomino; Gabriel Delgado García.

4 **Título del trabajo:** ARE THERE DIFFERENCES BETWEEN THE LEAD LIMBS DURING BLOCK JUMP-LANDING IN DIFFERENT DIRECTIONS?
Nombre del congreso: 24th annual congress of the European College of Sport Science
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: PRAGUE. CZECH REPUBLIC,
Fecha de celebración: 03/07/2019
Elia Mercado-Palomino; ALEJANDRO MOLINA MOLINA; Gabriel Delgado García.

5 **Título del trabajo:** Análisis del golpeo de padel remate por tres metros mediante el uso de giróscopos
Nombre del congreso: I Congreso de Investigadores del PTS
Tipo evento: Congreso **Ámbito geográfico:** Autonómica
Ciudad de celebración: Facultad de Medicina UGR,
Fecha de celebración: 13/02/2019
Gabriel Delgado García; Emilio José Ruiz Malagón; ALEJANDRO MOLINA MOLINA; Pablo Molina García; VICTOR MANUEL SOTO HERMOSO.

6 **Título del trabajo:** Validación de Wearables para el análisis técnico de tenistas
Nombre del congreso: XLI Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Madrid,
Fecha de celebración: 18/10/2018
Gabriel Delgado García; Emilio José Ruiz Malagón; ALEJANDRO MOLINA MOLINA; Elia Mercado-Palomino; VICTOR MANUEL SOTO HERMOSO.

7 **Título del trabajo:** Análisis de la trayectoria de la raqueta de tenistas ATP en competición mediante un sistema fotogramétrico 3D lowcost
Nombre del congreso: XLI Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Madrid,
Fecha de celebración: 18/10/2018
Gabriel Delgado García; Jose María Chicano Gutiérrez; Elia Mercado-Palomino; ALEJANDRO MOLINA MOLINA; Emilio José Ruiz Malagón; FRANCISCO JAVIER ROJAS RUIZ.

8 **Título del trabajo:** A Novel Automated Algorithm for Computing Lumbar Flexion Test Ratios Enhancing Athletes Objective Assessment of Low Back Pain
Nombre del congreso: International Congress on Sport Sciences Research and Technology Support (icSPORTS 2018)
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: Sevilla,
Fecha de celebración: 20/09/2018
Francisco Carrillo Pérez; ALEJANDRO MOLINA MOLINA; Diaz-reyes, Ignacio; Miguel Damas Hermoso; Oresti Baños Legrán; VICTOR MANUEL SOTO HERMOSO.

9 **Título del trabajo:** EFECTO DE LA APLICACIÓN DE TÉCNIAS DE BIOFEEDBACK PARA LA OPTIMIZACIÓN DE LA BIOMECÁNICA EN MARCHADORES DE ÉLITE
Nombre del congreso: Nuevas Tendencias Científicas Aplicadas al Entrenamiento de la Marcha
Tipo evento: Congreso **Ámbito geográfico:** Otros

Ciudad de celebración: Guadix (Granada),
Fecha de celebración: 09/12/2017
ALEJANDRO MOLINA MOLINA.

10 **Título del trabajo:** Sistema de evaluación de corredores basado en sensores inerciales
Nombre del congreso: XL CONGRESO DE LA SOCIEDAD IBÉRICA DE BIOMECÁNICA Y BIOMATERIALES
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 10/11/2017
Gabriel Delgado García; Elia Mercado-Palomino; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO.

11 **Título del trabajo:** Test específico de evaluación biomecánica de jugadores de tenis basado en sensores inerciales
Nombre del congreso: XL CONGRESO DE LA SOCIEDAD IBÉRICA DE BIOMECÁNICA Y BIOMATERIALES
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 10/11/2017
Gabriel Delgado García; Muñoz-garcía, Alejandro; Elia Mercado-Palomino; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO.

12 **Título del trabajo:** Desarrollo de un prototipo de exoesqueleto para la mejora de la eficiencia y la salud en gestos de locomoción del soldado de tierra (estudio piloto)
Nombre del congreso: XL CONGRESO DE LA SOCIEDAD IBÉRICA DE BIOMECÁNICA Y BIOMATERIALES
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 10/11/2017
ALEJANDRO MOLINA MOLINA; Elia Mercado-Palomino; Gabriel Delgado García; Gálvez-carmona, Juan José; Ramos-muños, Jose Luis; Roldán-aranda, Andrés; VICTOR MANUEL SOTO HERMOSO.

13 **Título del trabajo:** Differences between centre of mass in control and a random block jump in volleyball players
Nombre del congreso: International Congress Interdisciplinary Physical Prevention & Rehabilitation
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: Facultad de Ciencias del Deporte (Granada),
Fecha de celebración: 22/09/2017
Elia Mercado-Palomino; ALEJANDRO MOLINA MOLINA; Gabriel Delgado García; VICTOR MANUEL SOTO HERMOSO; AURELIO UREÑA ESPA.

14 **Título del trabajo:** The acute effect of the kinematic alterations produced in the increase of pace in endurance runners
Nombre del congreso: International Congress Interdisciplinary Physical Prevention & Rehabilitation
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: Facultad de Ciencias del Deporte (Granada),
Fecha de celebración: 22/09/2017
ALEJANDRO MOLINA MOLINA; Elia Mercado-Palomino; Gabriel Delgado García; Richards, Jim; VICTOR MANUEL SOTO HERMOSO.

15 **Título del trabajo:** Asimetrías y Evolución de la Masa Magra del brazo derecho en padelistas niños y adolescentes
Nombre del congreso: International Congress Interdisciplinary Physical Prevention & Rehabilitation
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: Facultad de Ciencias del Deporte (Granada),
Fecha de celebración: 22/09/2017
Gabriel Delgado García; ALEJANDRO MOLINA MOLINA; Muñoz -garcía, Alejandro; ALFONSO MAÑAS BASTIDAS; VICTOR MANUEL SOTO HERMOSO; FRANCISCO JAVIER OCAÑA WILHELMI; PABLO JESÚS GÓMEZ LÓPEZ.

16 **Título del trabajo:** Fatness and fitness in relation to functional movement in overweight/obese children: the MUBI project
Nombre del congreso: Interdisciplinary Physical Prevention & Rehabilitation
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: Granada, Andalucía, España,
Fecha de celebración: 22/09/2017
Pablo Molina García; Jairo Hidalgo Migueles; ALEJANDRO MOLINA MOLINA; Irene Esteban-Cornejo; Maria Rodriguez García; Gabriel Delgado García; Abel Plaza Florido; Cristina Cadenas Sánchez; Francisco B. Ortega Porcel.

17 **Título del trabajo:** CONCURRENT VALIDITY OF LOWER LIMB KINEMATICS BETWEEN MARKERLESS AND MARKER-BASED MOTION CAPTURE SYSTEMS IN GAIT AND RUNNING
Nombre del congreso: 35th International Conference on Biomechanics in Sport
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: COLONIA (ALEMANIA),
Fecha de celebración: 14/06/2017
ALEJANDRO MOLINA MOLINA; Elia Mercado-Palomino; Gabriel Delgado García; ANTONIO MILLÁN SÁNCHEZ; AURELIO UREÑA ESPA; VICTOR MANUEL SOTO HERMOSO.

18 **Título del trabajo:** Musculoskeleal pain is associated with current mental health in overweight/obese children: Preliminary results from the ActiveBrains project
Nombre del congreso: International symposium, ActiveBrains for all: Exercise, cognition and mental health
Tipo evento: Congreso **Ámbito geográfico:** Otros
Ciudad de celebración: Granada, Andalucía, España,
Fecha de celebración: 12/06/2016
Pablo Molina García; Jairo Hidalgo Migueles; ALEJANDRO MOLINA MOLINA; José Rafael Mora González; Irene Esteban-Cornejo; Maria Rodriguez García; Gabriel Delgado García; Abel Plaza Florido; Cristina Cadenas Sánchez; Francisco B. Ortega Porcel.

19 **Título del trabajo:** Efecto de la locomoción humana sobre el nivel de condición física en población mayor y su relación con la calidad de vida relacionada con la salud
Nombre del congreso: I Jornadas de Investigadores en Formación: Fomentando la Interdisciplinariedad
Tipo evento: Congreso
Ciudad de celebración: . UNIVERSIDAD DE GRANADA. GRANADA,
Fecha de celebración: 18/05/2016
ALEJANDRO MOLINA MOLINA; Gabriel Delgado García; VICTOR MANUEL SOTO HERMOSO.

20 **Título del trabajo:** Análisis biomecánico del golpeo y desplazamientos en pádel
Nombre del congreso: II Congreso nacional de investigacion en padel
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Granada,
Fecha de celebración: 05/05/2016

ALEJANDRO MOLINA MOLINA.

21 **Título del trabajo:** Análisis biomecánico de factores relacionados con el rendimiento y la condición física del jugador de pádel
Nombre del congreso: II Congreso nacional de investigacion en padel
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Granada,
Fecha de celebración: 05/05/2016
ALEJANDRO MOLINA MOLINA.

22 **Título del trabajo:** Relación de la Calidad de Vida Percibida con variables Baropodométricas en Estático y durante la locomoción en personas mayores
Nombre del congreso: First International Congress of Multidisciplinary Health Research
Tipo evento: Congreso
Ciudad de celebración: Jaén (Spain),
Fecha de celebración: 14/04/2016
Gabriel Delgado García; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO.

23 **Título del trabajo:** Influencia de la velocidad de carrera y la carrera calzada/descalza en relación al tipo de apoyo, inversión/eversión, y rotación vertical tibial en corredores de larga distancia
Nombre del congreso: XXXVIII Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 05/11/2015
ALEJANDRO MOLINA MOLINA; FELIPE GARCÍA PINILLOS; PEDRO ANGEL LATORRE ROMAN; VICTOR MANUEL SOTO HERMOSO.

24 **Título del trabajo:** 12 semanas de carrera descalzo: Efecto en apoyo inicial, grado de inversión-eversión y rotación del pie durante la carrera
Nombre del congreso: XXXVIII Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 05/11/2015
FELIPE GARCÍA PINILLOS; ALEJANDRO MOLINA MOLINA; PEDRO ANGEL LATORRE ROMAN; VICTOR MANUEL SOTO HERMOSO.

25 **Título del trabajo:** ¿Puede la cinemática explicar el fenómeno de potenciación post-activación en un salto vertical?
Nombre del congreso: XXXVIII Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 05/11/2015
FELIPE GARCÍA PINILLOS; ALEJANDRO MOLINA MOLINA; PEDRO ANGEL LATORRE ROMAN; VICTOR MANUEL SOTO HERMOSO.

26 **Título del trabajo:** Análisis de la cinemática de la carrera durante una media maratón. ¿Existe relación entre rendimiento y cinemática?
Nombre del congreso: XXXVIII Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 05/11/2015

ALEJANDRO MOLINA MOLINA; FELIPE GARCÍA PINILLOS; PEDRO ANGEL LATORRE ROMAN; VICTOR MANUEL SOTO HERMOSO.

27 **Título del trabajo:** Desarrollo de un protocolo de valoración musculoesquelética y del rendimiento deportivo de jugadores de pádel
Nombre del congreso: Congreso Nacional Real Federación Española de Tenis
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: . BARCELONA,
Fecha de celebración: 16/10/2015
Gabriel Delgado García; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO.

28 **Título del trabajo:** Comparación entre la derecha y el revés de tenis en cuanto a parámetros de precisión y velocidad y relación entre la velocidad y la precisión de golpeo
Nombre del congreso: XII Congreso Nacional de Tenis
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 16/10/2015
Gabriel Delgado García; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO.

29 **Título del trabajo:** Relación entre parámetros de fuerza del miembro superior y el rendimiento en un test específico de golpeo en tenis
Nombre del congreso: XII Congreso Nacional de Tenis
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Barcelona,
Fecha de celebración: 16/10/2015
Gabriel Delgado García; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO.

30 **Título del trabajo:** A Preliminary Study of the Relation between Back-Pain and Plantar-Pressure Evolution During Pregnancy
Nombre del congreso: Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE
Tipo evento: Congreso
Ciudad de celebración: Milan, Italy,
Fecha de celebración: 25/08/2015
FERNANDO MARTÍNEZ MARTÍ; MARÍA SOFÍA MARTÍNEZ GARCÍA; MIGUEL ÁNGEL CARVAJAL RODRÍGUEZ; ALBERTO JOSE PALMA LOPEZ; ALEJANDRO MOLINA MOLINA; VICTOR MANUEL SOTO HERMOSO.

31 **Título del trabajo:** Avances tecnológicos en biomecánica con sistemas basados en imagen.
Nombre del congreso: I Jornadas Nacionales de Biomecánica
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Zaragoza,
Fecha de celebración: 13/05/2015
ALEJANDRO MOLINA MOLINA.

32 **Título del trabajo:** Análisis de la técnica mediante fotogrametría
Nombre del congreso: I Congreso Nacional de Investigación en Pádel ¿Ciencia, Salud, Tecnología y Entrenamiento¿
Tipo evento: Congreso **Ámbito geográfico:** Nacional
Ciudad de celebración: Granada,
Fecha de celebración: 05/03/2015
ALEJANDRO MOLINA MOLINA.

33 **Título del trabajo:** Valoración Biomecánica Aplicada al Rendimiento Deportivo
Nombre del congreso: Congreso de Actividad fisica saludable, rendimiento deportivo y experiencias educativas en educación fisica
Tipo evento: Congreso
Ciudad de celebración: Ubeda (Jaen),
Fecha de celebración: 07/02/2015
Soto-hermoso, Victor; Heredia-jimenez, Jose; EVA ORANTES GONZALEZ; ALEJANDRO MOLINA MOLINA.

Otros méritos

Estancias en centros de I+D+i públicos o privados

Entidad de realización: University of Central Lancashire
Ciudad entidad realización: UNIVERSITY OF CENTRAL LANCASHIRE, PRESTON,
Fecha de inicio: 09/07/2018 **Duración:** 91 días
Tareas contrastables: Estancia en University of Central Lancashire. UNIVERSITY OF CENTRAL LANCASHIRE, PRESTON
Capac. adq. desarrolladas: Desarrollo Tareas para el Doctorado Internacional. Aprendizaje sobre tecnologías y análisis biomecánico: Qualisys y Visual3D.

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PLUS ULTRA

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