Tesis doctoral

Eficacia del empleo de tecnologías portables para la monitorización de indicadores de rendimiento y salud en tenistas

Efficacy of using wearables for monitoring performance and health indicators in tennis players

PROGRAMA DE DOCTORADO EN BIOMEDICINA
DEPARTAMENTO DE EDUCACIÓN FÍSICA Y DEPORTIVA
FACULTAD DE CIENCIAS DEL DEPORTE
UNIVERSIDAD DE GRANADA

Emilio José Ruiz Malagón

2024

Directores
Víctor Manuel Soto Hermoso
Gabriel Antonio Delgado García

Editor: Universidad de Granada. Tesis Doctorales
Autor: Emilio José Ruiz Malagón
ISBN: 978-84-1195-365-8
URI: https://hdl.handle.net/10481/92834

El doctorando / The doctoral candidate [**Emilio José Ruiz Malagón**] y los directores de la tesis / and the thesis supervisor: [**Víctor Manuel Soto Hermoso y Gabriel Delgado García**].

Garantizamos, al firmar esta tesis doctoral que el trabajo ha sido realizado por el doctorando bajo la dirección de los directores de la tesis y hasta donde nuestro conocimiento alcanza, en la realización del trabajo, se han respetado los derechos de otros autores a ser citados, cuando se han utilizados sus resultados o publicaciones. Y consideramos que el trabajo reúne las condiciones científicas necesarias, para hacer merecedor al estudiante del título de doctor, siempre y cuando así lo estime oportuno el tribunal.

Guarantee, by signing this doctoral thesis, that the work has been done by the doctoral candidate under de direction of the thesis supervisor/s and as far as our knowledge reaches, in the performance of the work, the rights of other authors to be cited (when their results or publications have been used) have been respected. And we consider that the work meets the necessary scientific conditions to earn the student the title of doctor, as long as the court deems it appropriate.

Lugar y fecha: 2 de enero de 2024, Granada.

Directores de la tesis: Doctorando:

Firma: Firma:

DEPARTAMENTO DE EDUCACIÓN FÍSICA Y DEPORTIVA

Facultad de ciencias de la actividad Física y el deporte

Universidad de Granada

Eficacia del empleo de tecnologías portables para la monitorización de indicadores de rendimiento y salud en tenistas

Efficacy of using wearables for monitoring performance and health indicators in tennis players

Emilio José Ruiz Malagón

Directores de la tesis doctoral:

Dr. Víctor Manuel Soto Hermoso
Catedrático de la Universidad
Universidad de Granada

Dr. Gabriel A. Delgado García
Prof. Contratado Doctor
Universidad Pontificia de Comillas

A todas aquellas personas que han sido la luz en mi camino

Especialmente a mi familia

UNIVERSIDAD DE GRANADA

ÍNDICE

ÍNDICE DE TABLAS

ÍNDICE DE FIGURAS

ABREVIATURAS

APA: Asociación Estadounidense de Psicología

CI: Coordinación intersegmentaria

DH: Revés a dos manos

ECG: Electrocardiograma

FCmax: Frecuencia cardiaca máxima

IMU: Inertial Measurement Unit

iMUDS: Instituto Mixto Universitario de Deporte y Salud

ITF: Federación Internacional de Tenis

MAPE: Media del porcentaje de error absoluto

OS: Sistema óptico de captura de movimiento

PPG: Fotopletismografía

PPP: Polar Precision Prime®

RMSE: Raíz del error cuadrático medio

Rω: velocidad angular resultante

SAS: Servicio Andaluz de Sanidad

SH: Revés a una mano

VO2max: consumo máximo de oxígeno

ω_{peak}: Pico de velocidad angular

GLOSARIO

Gold estándar: (del inglés patrón de oro) término utilizado para definir aquellos test o tecnologías que tienen contrastada la máxima precisión y fiabilidad a la hora de medir o evaluar una determinada patología o variable.

Escáner de luz estructurada: escáner 3D que proyecta un patrón de luz blanca o azul calibrada con alta precisión sobre el objeto o persona que se está escaneando. Normalmente, el patrón de luz se compone por líneas paralelas o en forma de cuadrícula.

Rigging: técnica que se utiliza en animación 3D para aportar la estructura a los diseños y configurarlos con el objetivo de obtener determinado tipo de movimientos en la animación. En el caso de personajes humanos, se podría definir como el proceso de añadirles huesos y esqueleto.

Skinning: se conoce como el proceso para asignar el *rigging* a una animación 3D. Existen diferentes posibilidades, como el que permite la deformación de la animación o los que permiten a los objetos 3D actuar como elementos sólidos o líquidos. En resumen, el *Skinning* es la relación de parentesco entre la animación 3D y su esqueleto donde el que manda es este último.

Lesión musculo-esquelética: Las lesiones musculo-esqueléticas son todas aquellas que incluyen roturas de huesos o dislocaciones de las articulaciones, distensiones, desgarros de ligamentos, esguinces y laceraciones de tendones.

Coordinación intersegmentaria: La coordinación intersegmentaria u óculo-manual describe la capacidad de utilizar los ojos y las manos durante diferentes trabajos motores. Se ha demostrado que la coordinación intersegmentaria se produce de proximal a distal en términos de velocidad angular y velocidad lineal en la mayoría de gestos técnicos de tenis.

Variabilidad motora: se puede definir como las similitudes y diferencias entre ensayos de una misma tarea. Por ejemplo, dos derechas de tenis realizadas de forma consecutiva tienen algo en común y algo diferente. Es decir, los sistemas biológicos tienen la capacidad de adaptarse a los condicionantes externos y esto es gracias a que poseen la característica de la variabilidad.

Evaluación integral: tipo de evaluación multidisciplinar realizada a deportistas que tiene en cuenta aspectos como la eficiencia biomecánica y fisiológica, aspectos psicosociales, la destreza táctica y el método de enseñanza-aprendizaje, con el objetivo de fomentar una práctica deportiva saludable y optimizar el rendimiento.

Velocidad angular: es una medida de la velocidad de rotación. Se entiende como el ángulo girado por unidad de tiempo y se simboliza con la letra griega ω. Su unidad en el Sistema Internacional es el radián por segundo (rad/s).

Sistema óptico de captura de movimiento: se basan en un conjunto de cámaras, generalmente infrarrojas, que se emplean para captar el movimiento de un sujeto y un software que los interpreta. De este modo, las cámaras registran y aplican los movimientos a un modelo digital. Los sujetos que realizan los movimientos a capturar, suelen llevar puesto un traje con marcadores reflectantes que permite a las cámaras detectarlos con alta precisión.

Asesor virtual: son tutores que muestran ejemplos y realizan demostraciones, empleando: infografías 3D con actores sintéticos (avatar 3D); realidad aumentada; realidad virtual; proporcionan biofeedback a tiempo real de indicadores de salud y rendimiento; gestionan alertas y avisos, en caso de consecución de hitos o bien cuando se superen umbrales; interaccionan con los wearables; gestionan refuerzos positivos.

Tecnología wearable: o tecnología vestible, son aquellos dispositivos electrónicos que se colocan en el cuerpo humano y que interactúan con otros aparatos para transmitir o recoger algún tipo de dato. Por ejemplo, un reloj deportivo colocado al tenista para medir su frecuencia cardiaca durante los entrenamientos.

PREÁMBULO

La presente tesis doctoral representa un avance en la monitorización de parámetros de rendimiento y salud en tenistas mediante tecnologías portables. Se llevó a cabo dentro del grupo de investigación CTS-545 "Human and Motion Lab" (https://www.humanlabugr.com/), perteneciente al departamento de Educación Física y Deportiva de la Facultad de Ciencias de la Actividad Física y el Deporte (Universidad de Granada).

Se ha contado con la financiación y apoyo de los siguientes proyecto e instituciones a lo largo de su desarrollo:

- Fondo Europeo de Desarrollo Regional (FEDER) (DEP2015-70980-R y PID2020-115600RB-C21).
- Convocatoria de Proyectos de Investigación del Centro Mixto Universidad de Granada y el Mando de Adiestramiento y Doctrina del Ejército de Tierra Español (CEMIX UGR-MADOC) (CEMIX 22-16 y CEMIX 9/18).
- Programa Estatal de Infraestructuras Científicas y Técnicas y Equipamiento (Plan Estatal de I+D+i) del Ministerio de Economía y Competitividad (Ref.: UNGR15-CE-3400 y EQC2018-004702-P).
- Transferencia de Conocimiento entre los Agentes del Sistema Andaluz del Conocimiento y el Tejido Productivo, Plan Andaluz de I+D+I (PAIDI 2020) (5974).
- Ministerio de Educación y Formación Profesional (IAFP21/00141).
- Fondos europeos (NextGenerationEU) del Plan de Recuperación, Transformación y Resiliencia para el año 2022. Organismo: Consejo

Superior de Deportes, Ministerio de Cultura y Deporte (EXP_74829 y ActiVital).

- Junta de Andalucía, a través de un Convenio Específico entre la Consejería de Turismo, Cultura y Deporte de la Junta de Andalucía (Dirección General de "Sistemas y Valores del Deporte") (AndalucíaMuévete_Mayores).

A través de un análisis integral del tenista se han publicado 4 artículos, 3 de ellos JCR (los cuales avalan el presente trabajo), con el objetivo de tener la mayor información posible de cara al desarrollo final de una aplicación móvil innovadora, basada en el uso de asesores virtuales.

RESUMEN GENERAL (ESPAÑOL E INGLÉS)

Las nuevas tecnologías portables cada vez son más utilizadas en deportes de raqueta. Sus aplicaciones abarcan el análisis cinemático y cinético, la evaluación de parámetros fisiológicos, el estudio de aspectos psicológicos, la optimización del rendimiento y la prevención de lesiones musculo-esqueléticas. Por ello, en la presente tesis se han desarrollado 4 estudios encaminados a la creación final de una aplicación de análisis integral basada en asesores virtuales de tenis.

Los objetivos de la presente tesis fueron: i) evaluar la validez y fiabilidad de tecnologías wearables aplicables al tenis *(estudios 1 y 2)*; ii) utilizar de forma aplicada tecnologías wearables para obtener conclusiones de importancia biomecánica en situaciones reales de juego en tenis *(estudios 3 y 4);* iv) desarrollar una aplicación móvil basada en el uso de asesores virtuales con todos los datos obtenidos en los distintos estudios.

Se utilizaron dos tipos de metodologías: se realizaron protocolos de evaluación en condiciones de laboratorio (estudio 2). Ya que en este caso fue necesaria la utilización de un sistema de referencia no portable para la validación de los sensores utilizados. Por otro lado, en el resto de estudios *(estudios 1, 3 y 4),* la metodología se basó en protocolos de evaluación en pista mediante el desarrollo de tests de golpeo y planificación de sesiones de entrenamiento estandarizadas.

Los resultados demuestran la eficacia de las nuevas tecnologías wearables utilizadas en el presente trabajo, para monitorizar parámetros biomecánicos y fisiológicos en tenistas. En cuanto a las dos validaciones de tecnologías wearables (*estudios 1 y 2*), ambas resultaron ser herramientas

válidas y fiables para medir frecuencia cardiaca y cinemática durante la práctica del tenis, respectivamente. Con los *estudios 3 y 4* se consiguió obtener conclusiones de valor biomecánico mediante la aplicación de campo de las tecnologías wearables. Concretamente, se evaluaron las diferencias entre el revés a una y dos manos en términos de velocidad, precisión y cinemática *(estudio 3).* Por otro lado, se midió la variabilidad motora de los golpes principales de tenis en función del tipo de golpe, nivel de juego y segmento corporal del tenista *(estudio 4).*

En conclusión, los sistemas wearables utilizados constituyen una alternativa, de bajo coste y fácil configuración y uso. Además, aportan parámetros medidos en situaciones reales de juego, lo cual supone una gran ventaja frente a los sistemas tradicionales de evaluación en condiciones de laboratorio. Finalmente, la aplicación desarrollada se deberá seguir perfeccionando, mediante la implementación de todos los datos recogidos en los estudios y de nuevas funcionalidades con el objetivo futuro de evaluar con un estudio longitudinal como afecta su uso al proceso de aprendizaje global del tenis. Lo cual, la confirmaría como un valioso instrumento para entrenadores, jugadores e investigadores de tenis y en un futuro, adaptable a cualquier otro deporte de raqueta.

Palabras clave: wearable; deportes de raqueta; IMU; biomecánica; tenis; fisiología.

New portable technologies are increasingly used in racquet sports. Its applications cover kinematic and kinetic analysis, the evaluation of physiological parameters, the study of psychological aspects, the optimization of performance and the prevention of musculoskeletal injuries. For this reason, in this thesis 4 studies have been developed aimed at the final creation of a comprehensive tennis player analysis application based on virtual advisors.

The objectives of this thesis were: i) evaluate the validity and reliability of wearable technologies applicable to tennis (*studies 1 and 2*); ii) use wearable technologies in an applied manner to obtain conclusions of biomechanical importance in real tennis game situations (*studies 3 and 4*); iv) develop a mobile application based on the use of virtual advisors with all the data obtained in the different studies.

Two types of methodologies were used: evaluation protocols were carried out under laboratory conditions (*study 2*). Since in this case it was necessary to use a non-portable reference system for the validation of the sensors used. On the other hand, in the rest of the studies (*studies 1, 3 and 4*), the methodology was based on on-court evaluation protocols through the development of stroke tests and planning standardized training sessions.

The results demonstrate the effectiveness of the new wearable technologies used in the present work, to monitor biomechanical and physiological parameters in tennis players. Regarding the two validations of wearable technologies (*studies 1 and 2*), both turned out to be valid and reliable tools to measure heart rate and kinematics during tennis practice, respectively. With studies 3 and 4, conclusions of biomechanical value were obtained through the field application of wearable technologies. Specifically, the differences between the one-handed and two-handed backhand were evaluated in terms of speed, precision and kinematics (*study 3*). On the other hand, the motor variability of the main tennis strokes was measured depending on the type of stroke, level of play and body segment of the tennis player (*study 4*).

In conclusion, the wearable systems used constitute an alternative, low cost and easy to configure and use. In addition, they provide parameters measured in real game situations, which is a great advantage over traditional evaluation systems in laboratory conditions. Finally, the developed application must continue to be perfected, through the implementation of all the data collected in the studies and new functionalities with the future objective of evaluating with a longitudinal study how its use affects the global learning process of tennis. Which would confirm it as a valuable instrument for tennis coaches, players and researchers and, in the future, adaptable to any other racket sport.

Keywords: wearable, racket sports; IMU; biomechanics; tennis; physiology

INTRODUCCIÓN GENERAL

1. INTRODUCCIÓN GENERAL

1.1. EL TENIS Y EL RESTO DE DEPORTES DE RAQUETA EN LA SOCIEDAD ACTUAL

En los últimos años los deportes de raqueta han ido adquiriendo importancia respecto a los deportes más practicados tradicionalmente, ya que ha aumentado significativamente el número de personas que los practican. Debido a lo anterior, el interés científico por los deportes de raqueta también ha incrementado (1). Existen numerosas disciplinas dentro de los deportes de raqueta: tenis, tenis de mesa, pádel, squash, bádminton, tenis playa, etc. Todas ellas comparten ser disciplinas con esfuerzos interválicos de moderada y alta intensidad, provocados por ejecuciones repetitivas de corta duración, pero de alta intensidad (2, 3). Los deportes de raqueta se pueden dividir en función del tipo de pista donde se desarrolla el juego. Los principales se practican en una superficie dividida por una red (tenis, bádminton y tenis de mesa); otros requieren de un muro o valla (frontenis y squash); y mixtos, donde existe la división de la red además de paredes traseras y frontales (pádel) (1).

Los deportistas de raqueta tanto principiantes como profesionales, deben saber que para conseguir un adecuado rendimiento tendrán que atender a la aptitud y preparación psicológica, la condición física, la conciencia táctica y la eficiencia biomecánica y fisiológica (4). En un partido individual de cualquier disciplina de raqueta dos jugadores alternan el golpeo de la pelota, comenzando con el servicio de uno de ellos y terminando con un jugador que anota un punto. Esta serie de golpeos alternativos se llama rally. Ambos jugadores habrán de analizar múltiples variables en cada uno de sus golpeos (técnica a utilizar, posición de la pelota, posición en la pista del rival, etc.).

La práctica de deportes de raqueta tiene beneficios tanto para jóvenes como adultos. En el caso de los jóvenes, contribuyen al desarrollo de habilidades perceptivo-motrices, al control motor, lateralidad, la motivación y promueven el aprendizaje (5, 6). Además, cualquier persona puede practicarlos independientemente de sus cualidades físicas o intelectuales (7), por lo cual, favorecen la integración de estudiantes con discapacidad intelectual leve ayudando a su normalización socialización y no discriminación por parte de sus iguales (8). En cuanto a los beneficios para la salud en adultos a nivel recreacional, también resultan de especial interés para poblaciones con problemas mentales ya que no requieren de adaptaciones y son inclusivos (9). Igualmente, la práctica regular de algún tipo de deporte de raqueta reduce en un 47% el riesgo de sufrir un infarto o una enfermedad cardiovascular (10), mejoran la capacidad aeróbica, reducen el índice de masa corporal y mejoran de la salud ósea (11, 12). Por tanto, en función de todos los beneficios que reportan e impacto en la sociedad actual, se deberá fomentar la práctica de deportes de raqueta en cualquier tipo de población independientemente de su nivel, edad, género o raza.

A nivel mundial la práctica del tenis está muy extendida con un total de 75 millones de jugadores aproximadamente (12, 13), solo en España alrededor de 3 millones de personas lo practican al menos dos veces al mes; existiendo un total de 80.318 licencias de competición en 2023 según la Real Federación Española de Tenis (14). Este popular deporte se práctica sobre pista (dura, tierra, césped y moqueta). Las dimensiones de una pista reglamentaria son 23.77 m x 8.23 m para simples y 23.77 m x 10.97 m para dobles. La red que divide la pista en dos partes igual se coloca a una altura de

0.941 cm. En el tenis, el implemento utilizado es la raqueta, que se fabrican con titanio, grafito y fibra de vidrio. Una raqueta para adulto tiene una longitud de entre 67cm y 73 cm, siendo la longitud máxima permitida 81,28 cm. Las cuerdas de las raquetas se fabrican con nailon o tripa resistente. En cuanto a la pelota utilizada, es hueca y se fabrica con caucho y una cubierta de tela. La pelota de tenis puede llegar a alcanzar 250 km/h en un saque de jugador profesional.

El tenis, al igual que el resto de deportes de raqueta, tiene beneficios para la salud, como son la mejora de la capacidad aeróbica, reducción del porcentaje de grasa corporal, mejora el perfil lipídico, reduce el riesgo de enfermedad cardiovascular y mejora la salud ósea (10, 12). Sin embargo, su práctica también conlleva un riesgo de lesión como ocurre en el resto de deportes. Un metaanálisis realizado por Pluim et al., (15) concluyó que el rango de aparición de una lesión en tenis va del 0.04% al 3% por cada 1000 horas de juego. Las lesiones más frecuentes son las de extremidades inferiores (31% al 67%), seguidas de las lesiones de extremidades superiores (20% a 49%) y, por último, las menos frecuentes son las lesiones de tronco (3% al 21%) (15–17). Dentro de las lesiones de tren inferior las más comunes son las de tobillo y muslo; en cuanto a las de tren superior las de hombro y codo; y las lesiones de lumbares serían las lesiones más frecuentes de tronco. Concretamente, las roturas musculares, la inflamación y los esguinces son las lesiones más habituales en tenis (17, 18).

1.2. BIOMECÁNICA DEL TENIS

La biomecánica en tenis juega un papel integral en la producción de los distintos tipos de golpeo (derecha, revés, servicio, volea, etc.), además de ser un factor clave para el éxito del jugador tanto a nivel competitivo como recreacional (19, 20). Todos los golpeos en tenis están fundamentados en un patrón mecánico (entendido como el gesto técnico individual de cada jugador). Las lesiones deportivas dentro de esta disciplina también tienen principalmente una causa mecánica, de aquí su importancia (20, 21). Por lo tanto, los objetivos principales del biomecánico deportivo son mejorar el rendimiento y reducir el riesgo de lesión del jugador. Los estudios biomecánicos de tenis se centran en analizar la cinemática y cinética de los distintos golpeos mediante grabaciones 3D, medición de la activación muscular (electromiografía) o simulaciones y modelaje (22, 23).

La ejecución técnica de todos los golpes de tenis consta de 3 fases: preparación, aceleración y terminación (24). La coordinación entre las distintas fases del golpeo, la coordinación óculo-manual y las conexiones intersegmentarias serán los factores claves para la consecución una técnica adecuada de golpeo (19,20,23). Se ha demostrado que la coordinación intersegmentaria (CI) se produce de proximal a distal en términos de velocidad angular y velocidad lineal (25) en la mayoría de golpeos del tenis y que el momento de máxima rotación del tronco adquiere un carácter fundamental en el rendimiento que se puede llegar a alcanzar en el golpe (26). Otra variable que determina la eficiencia biomecánica del jugador será la variabilidad motora en los distintos tipos de golpeo, ya que una menor variabilidad (entendida como baja variación entre una derecha y otra, por ejemplo) se asocia con jugadores de mayor nivel y viceversa (27). A continuación, se describe la cinemática y cinética de los principales golpes de tenis.

1.2.1. Saque

El saque en tenis es el golpeo más importante ya que es el que más puntos otorga al jugador durante los partidos y además comienza todos los puntos (28). Durante el servicio, el jugador comienza desde posición estática y realiza una serie de movimientos coordinados de la parte inferior y superior del cuerpo en un periodo ligeramente superior a 1s, resultando un golpeo de pelota que puede llegar a alcanza 240 km/h. Se trata pues de un movimiento explosivo que requiere de potencia y aceleración. La técnica de saque en tenis está basada en una cadena cinética que lo divide en cuatro fases: toma de impulso, preparación, aceleración y terminación (29, 30) (figura 1).

Figura 1. Fases del saque de tenis

La fase de "toma de impulso" comienza desde posición estática (preparado para sacar), y termina con la liberación de la pelota desde la mano no dominante. Durante esta fase, cada jugador adquiere sus propias peculiaridades técnicas existiendo así múltiples tipos de tomas de impulso distintas. El aspecto más importante de esta fase será lanzarse la pelota lo mejor posible (con trayectoria lo más rectilínea posible) con el objetivo de conseguir un punto de impacto óptimo. En esta fase se inicia el almacenamiento de energía potencial que posteriormente se transferirá a través de la cadena cinética (29, 31).

La fase de "preparación" comienza con el lanzamiento de la pelota de la mano no dominante y finaliza en el punto de máxima rotación externa del hombro dominante. Esta fase se divide en "preparación temprana" y "preparación tardía". Durante la "preparación temprana" el brazo comienza a rotar de forma externa y los tobillos se flexionan con el objetivo de tomar impulso del suelo (32). En la "preparación tardía" las piernas comienzan a subir antes de que el brazo no dominante comience a rotar de forma interna, lo que provoca una mayor rotación externa del hombro y, por lo tanto, un almacenamiento de energía de los músculos implicados. También durante esta fase, el cuerpo se aleja de la red, al mismo tiempo que las rodillas y las caderas del jugador se flexionan. La espalda se extiende y gira alejándose de la red. Los movimientos anteriores conllevan a que aumente la energía potencial almacenada (29, 31).

La fase de "aceleración" comienza desde el momento de máxima rotación externa del brazo dominante hasta el punto de impacto con la pelota y también se puede dividir en fase "temprana" y "tardía". Durante la "aceleración temprana" la energía potencial almacenada en las estructuras elásticas pasivas del hombro, codo y espalda se convierte en energía cinética.

Al mismo tiempo, las rodillas y las caderas se extienden, además la espalda se mueve pasando de extensión a flexión y girando hacia el lado no dominante "aceleración tardía". Durante esta fase el hombro y el codo obtienen la máxima activación muscular a la que llegarán durante el gesto técnico (33). Finalmente, la fase de "terminación" comienza con el contacto con la pelota y acaba con el final del gesto técnico. En el momento del impacto se liberan todas las fuerzas acumuladas y transferidas a través de los distintos segmentos corporales intervinientes en la cadena cinética del saque de tenis.

Para finalizar la presente sección, se han demostrado diferencias biomecánicas significativas en función del efecto que se imprime a la pelota durante el saque, existiendo el saque plano (mayor potencia) y los saques con efecto liftado y cortado (mayor control) (31).

1.2.2. Derecha

El golpe de derecha ocupa un lugar muy cercano en importancia al saque tanto para investigadores como entrenadores (34). Es el segundo golpe más estudiado del tenis ya que numerosos artículos han descrito su biomecánica (20, 35–37). Los estudios sobre la derecha se han centrado en la precisión del golpeo, coordinación, consistencia, generación de velocidad de pelota y producción de efecto (38). El gesto técnico de la derecha de tenis se puede dividir en 3 fases: preparación, aceleración y terminación (35) (figura 2).

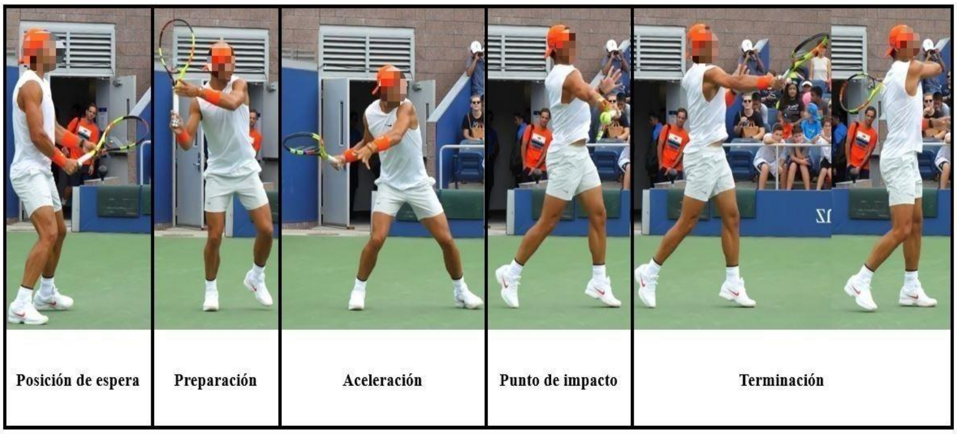


Figura 2. Fases de la derecha de tenis

Antes de realizar cualquier golpeo de tenis se debe partir de “posición de espera”. Dicha posición, se caracteriza por tener las piernas abiertas a la anchura de los hombros y las manos sosteniendo la raqueta a la altura de la cintura. El cuerpo se inclina ligeramente hacia delante para concentrar el peso en las puntas de los pies y así tener una mayor capacidad de reacción. La fase de “preparación” empieza con el movimiento del brazo dominante hacia atrás y la flexión de las rodillas y la cadera, de modo que el cuerpo se acelera en dirección a la pista. A continuación, se produce una deceleración que provoca un estiramiento de los músculos, que induce el almacenamiento de energía elástica en los segmentos implicados en el movimiento (39). La energía almacenada ayuda al impulso de las extremidades inferiores hacia la pelota. Esta fase presenta distintos patrones en función del jugador y su nivel de juego, al igual que la fase de “toma de impulso” del saque. Desde la posición anterior, se produce un giro del pie trasero y un movimiento hacia atrás del codo sincronizado con la rotación del hombro, de modo que la raqueta queda apuntado a la pelota que se aproxima. Luego, se cierra la cabeza de la raqueta mientras el codo se eleva. A continuación, el antebrazo y la raqueta giran alrededor del codo y el hombro (rotación externa del húmero), esto provoca que la raqueta gire hasta una posición por encima del codo y el hombro (40).

La fase de “aceleración” empieza con el primer movimiento hacia delante de la raqueta. La rodilla delantera y la cadera se extienden desde la posición de “preparación” hasta el impacto. Al mismo tiempo, el hombro se eleva ayudando a que la trayectoria de la raqueta tenga una línea ascendente. Se produce una rotación del tronco y un impulso de las extremidades inferiores que provoca un aumento del giro de hombro dominante que ayuda a la aceleración de la raqueta hacia delante. Durante esta fase, se produce una transmisión de los pesos hacia el pie más adelantado. Finalmente, el codo se extiende y el ángulo de la muñeca disminuye justo antes del impacto. En este momento, se registran en el antebrazo las velocidades angulares máximas del gesto técnico (39).

Tras el “impacto” la raqueta pierde aproximadamente el 80% de su velocidad, entrando así en la fase de “terminación”, donde se produce una deceleración gradual de los segmentos mientras que la pierna trasera se adelanta y se vuelve a colocar al nivel del pie delantero, quedando el jugador preparado para en el siguiente golpeo (“posición de espera”). Se deberá tener en cuenta que el gesto técnico desarrollado podría cambiar en función del efecto deseado, la dirección de la pista a la que se quiere enviar la pelota o el nivel de juego del jugador ya que se ha demostrado que afectan significativamente a la biomecánica de la derecha de tenis (36–40).

1.2.3. Revés a una y dos manos

A pesar de que la derecha permite generar más velocidad, efecto y precisión después del golpe que el revés, este también es uno de los tres tipos de golpeo principales del tenis (saque, derecha y revés) y está cobrando cada vez más importancia en el tenis moderno (41–43). Para un jugador la elección de usar el revés a una (SH) o dos manos (DH) es un punto clave, ya que en función de esta decisión alcanzará una mayor o menor eficiencia biomecánica en base a sus características (26). Al igual que la derecha, ambos tipos de revés se realizan en tres fases: “preparación” comienza con el movimiento de la raqueta hacia atrás y finaliza cuando la raqueta invierte su dirección moviéndose hacia delante; “aceleración” que acaba en el momento del impacto de la raqueta con la pelota; “terminación” que implica detener el movimiento progresivamente una vez se ha golpeado la pelota (figura 3) (44).

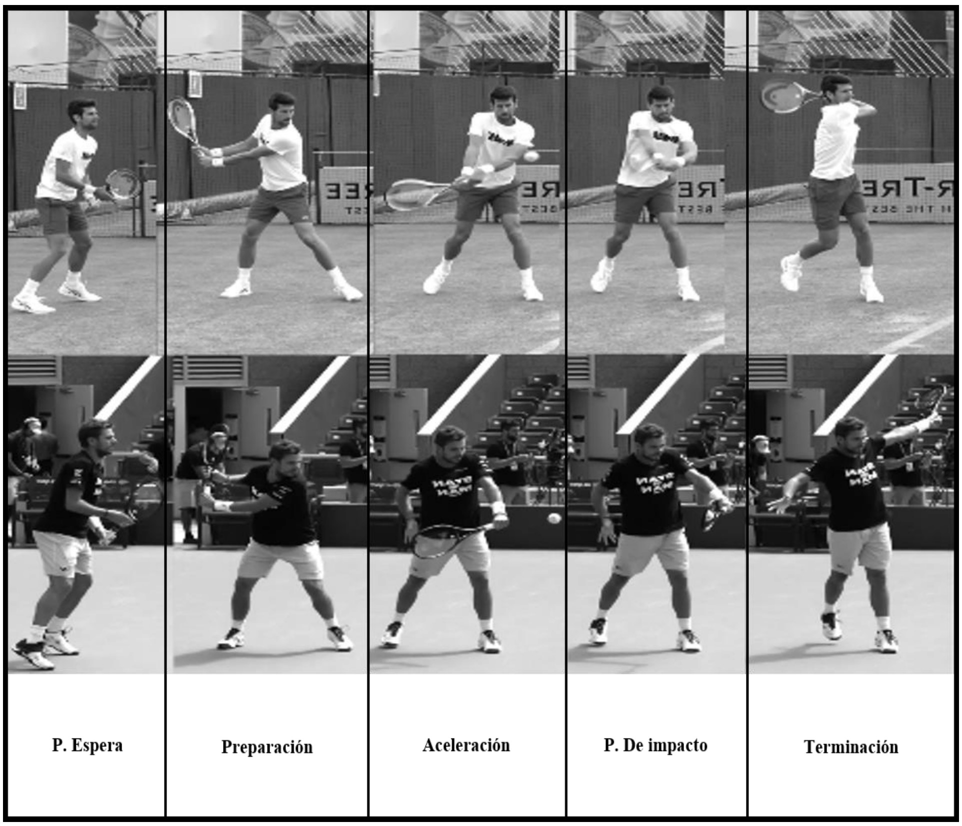


Figura 3. Fases del revés a una y dos manos de tenis

El DH es el revés que suelen elegir los jugadores de fondo, es decir, que prefieren que los peloteos sean largos y evitan subir a la red con mucha frecuencia. En cambio, SH lo suelen utilizar jugadores más versátiles ya que con él se consiguen más fácilmente golpes de aproximación a la red (26). Por otro lado, DH se utiliza más durante las fases de iniciación ya que requiere menos fuerza que el SH (45). Otro factor que favorece la selección del DH en jugadores principiantes adultos es que el SH es más susceptible a la lesión “codo de tenista” (45, 46). En cambio, no se han demostrado diferencias en términos de precisión y velocidad de pelota entre ambos tipos de revés.

Se han demostrado diferencias biomecánicas significativas entre ambos tipos de revés en términos de parámetros cinéticos y cinemáticos (47). El DH produce mayores movimientos de rotación (rad/s) sobre el eje longitudinal durante la fase de “preparación”, ya que este tipo de revés genera mayores rotaciones de tronco y rotaciones externas del brazo y antebrazo que el SH (48). En cambio, el revés a una mano registra picos de velocidad angular (rad/s) mayores sobre el eje transversal del movimiento en el brazo y antebrazo del jugador, lo que se traduce en una mayor extensión del antebrazo durante la fase de “terminación” del gesto técnico (49). Finalmente, como se puede apreciar en la figura 3, el punto de impacto es más adelantado respecto al tronco en el SH que en el DH (50).

1.3. FISIOLOGÍA DEL TENIS

El tenis se caracteriza por esfuerzos de alta intensidad como cambios de dirección, aceleraciones, desaceleraciones e implicaciones de la parte superior del brazo dominante. Los esfuerzos de alta intensidad se intercalan con periodos de baja intensidad de duración variable (recuperación activa entre puntos de 20s y periodos sentados de entre 90s y 120s durante los cambios de campo) (51–53). Además, se requiere del jugador un rápido procesamiento perceptivo-motor y una ejecución técnica con la mayor combinación posible de velocidad y precisión resultante de la pelota (51–53). Desde un enfoque fisiológico, el tenis supone ejercitarse a intensidades medias en torno al 70-90% de la frecuencia cardiaca máxima (FCmax) y al 50-60% del consumo máximo de oxígeno (VO2max), aunque estas estimaciones medias pueden verse afectadas por rallies de larga duración, el tipo de pista o pelota (aumento de la FCmax y VO2max) (42, 52, 54).

Como ya se ha explicado, el rendimiento en tenis tiene un carácter multifactorial. Durante un partido los elementos fisiológicos, biomecánicos, psicológicos y perceptivos se integran determinando el resultado del partido. Además de las variables de rendimiento, influyen las condiciones ambientales como la superficie de juego, duración de los partidos y estrategias de juego. La combinación de todas las variables anteriores provoca en los jugadores una tensión fisiológica que evoluciona involuntariamente (fatiga, hipertermia, deshidratación o hipoglucemia) (55). Dichas alteraciones homeostáticas suelen afectar directamente al desarrollo de los partidos tanto a nivel recreacional como competitivo (56). Por lo tanto, se hará de vital importancia el análisis fisiológico de nuestros jugadores durante los entrenamientos y partidos.

En el presente trabajo, la variable fisiológica que será objeto de estudio y análisis es la frecuencia cardíaca. La elección de la frecuencia cardíaca como variable fisiológica clave se basa en su capacidad para proporcionar información crucial sobre la respuesta cardiovascular del organismo durante la práctica del tenis (57). La frecuencia cardíaca es un indicador sensible y rápido de la demanda cardiovascular, reflejando la intensidad del esfuerzo físico en tiempo real. En el contexto del tenis, un deporte dinámico y exigente desde el punto de vista cardiovascular, la frecuencia cardíaca se convierte en un marcador valioso para evaluar el esfuerzo físico y la respuesta del sistema cardiovascular durante diferentes fases del juego, como el calentamiento, la parte principal y la vuelta a la calma (entrenamientos), e incluso durante los partidos de competición (57, 58). La monitorización continua de la frecuencia cardíaca en el tenis también puede contribuir a la prevención de lesiones y al ajuste del nivel de esfuerzo según las capacidades individuales de los jugadores (59). Asimismo, puede proporcionar datos valiosos para comprender mejor la respuesta cardiovascular ante factores como el estrés competitivo, la fatiga y otros elementos psicofisiológicos relacionados con la práctica del tenis (59, 60).

1.4. PROCESOS DE ENSEÑANZA-APRENDIZAJE DE LA TÉCNICA EN TENIS

Se ha demostrado que para llegar a ser profesional o conseguir un rendimiento de competición en tenis se necesitan años de práctica sostenida. Además, existen escasas soluciones que reduzcan ese tiempo de adquisición de la excelencia deportiva (61). Con el objetivo de producir más y mejores jugadores los científicos de ciencias del deporte han buscado intensamente los ingredientes que mejoren el rendimiento y salud de los jugadores tanto en iniciación como élite. Se publican multitud de artículos analizando la biomecánica y fisiología del tenis, sin embargo, el análisis de otras disciplinas implicadas como el aprendizaje motor y la psicología han recibido menos atención en investigación comparativamente (57, 58). La creación de enfoques modernos en el desarrollo de planes de entrenamiento de tenis se vuelve de vital importancia para mejorar los niveles de coordinación y motivación de los jugadores. Además, ayudan a los entrenadores a proyectar de forma más adecuada los aspectos para incluir y mejorar sus planificaciones deportivas (62).

En conjunto, la forma en que el entrenador estructura la práctica, presenta la información y da feedback a los jugadores puede considerarse “su enfoque de entrenamiento” (61). La Federación Internacional de Tenis (ITF) en su libro “Advanced Coaches Manual” distingue entre los siguientes enfoques de entrenamiento de tenis: estilo de enseñanza prescriptivo o por descubrimiento; método de enseñanza global o analítico; tipo de liderazgo que incluye autoritario, cooperativo y casual (63). En resumen, la literatura actual divide entre entrenamiento prescriptivo, por descubrimiento o combinaciones de ambos. En su estudio de William et al. (64), demostraron que tanto la instrucción prescriptiva como por descubrimiento guiado tienen éxito mejorando la capacidad de reacción, anticipación y precisión de golpeo en una muestra de jugadores jóvenes en fase de iniciación. En cambio, Smeeton et al. (64) también compararon ambos enfoques en relación a la capacidad anticipatoria y coordinación motora en una muestra de jugadores jóvenes de nivel intermedio, obteniendo que el grupo instruido mediante aprendizaje guiado y aprendizaje por descubrimiento tuvo respuestas significativamente más rápidas que el grupo con enfoque prescriptivo.

Se ha demostrado que la incorporación en los planes de entrenamiento de tareas que impliquen coordinación motora (62) y fomento de la motivación (65) en edades tempranas de aprendizaje pueden mejorar la condición física, ejecución técnica de los distintos golpeos y el clima motivacional en tenis. En conclusión, cuando se diseña un plan de entrenamiento en tenis se deberá abordar desde un enfoque integral que incluya todas las necesidades específicas de nuestros jugadores para que así puedan mejorar su juego de forma eficaz (figura 4).

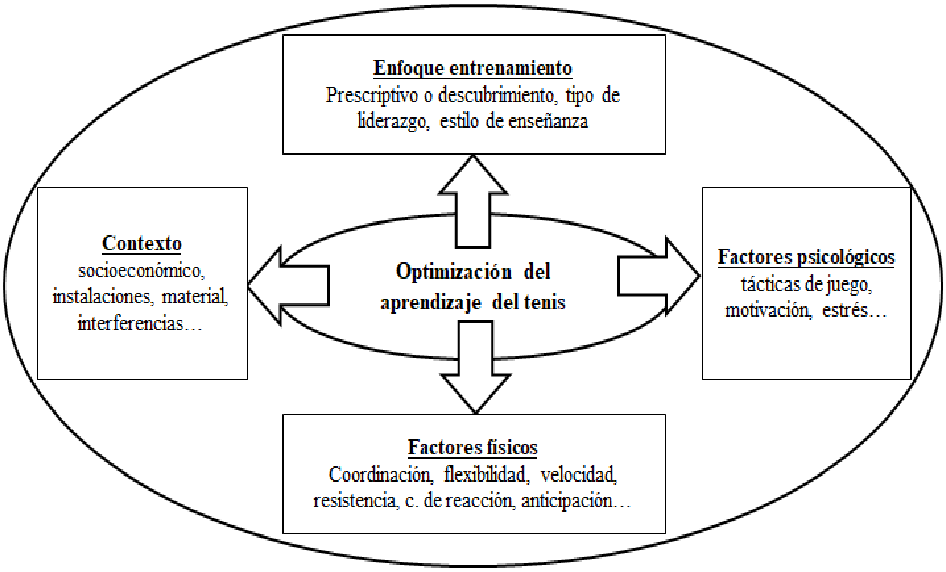


Figura 4. Diagrama de las variables principales para la optimización del aprendizaje del tenis

1.5. NUEVAS TECNOLOGÍAS APLICADAS AL TENIS

Nuestro mundo actual está dominado por las nuevas tecnologías, vivimos en la denominada "revolución digital" donde prácticamente todas las personas hacen uso de la tecnología en algún contexto de sus vidas. Su uso en las últimas décadas, es cada vez más emergente en los distintos deportes ya que bien utilizadas, las nuevas tecnologías pueden constituir nuestra mejor herramienta para mejorar el rendimiento y salud (prevención de lesiones musculo-esqueléticas) de nuestros deportistas (66).

En ciencias del deporte, existen dos tipos de tecnologías en función de su portabilidad: tecnologías portables o wearables y no portables. Se entiende por tecnología portable o wearable (vestible) todos aquellos dispositivos electrónicos que se usan en el cuerpo humano y que interactúan con otros aparatos para transmitir o recoger algún tipo de datos. Además, es aquella que se puede utilizar en situaciones ecológicas, es decir, en situaciones reales de juego. Un ejemplo muy utilizado de wearable lo constituyen los relojes inteligentes y las pulseras de actividad. Por ejemplo, un reloj deportivo colocado en la muñeca de nuestro tenista durante un entrenamiento o partido. En cambio, se entiende por tecnologías no portables aquellas que no tienen posibilidad de usarse en situaciones de campo. Por lo tanto, se utilizan en contextos de laboratorio. Por ejemplo, realizando un análisis biomecánico de nuestro jugador mediante fotogrametría 3D. Si se comparan las ventajas e inconvenientes de cada una de ellas tenemos que las tecnologías portables tienen mayor portabilidad, fácil configuración y uso y un menor coste económico, mientras que las tecnologías no portables, son más precisas (67).

Cada vez es más frecuente el uso de las nuevas tecnologías por parte de entrenadores, jugadores, sanitarios y científicos en tenis (68–71). Actualmente, se utilizan para analizar cualquier variable del juego y del jugador: análisis cinemático (50) y cinético (72) de la técnica de los distintos golpes del jugador; fomento del rendimiento (73) (velocidad de pelota y precisión); monitorización de parámetros fisiológicos (74) (carga externa e interna, frecuencia y variabilidad cardiacas); reducción del riesgo de lesión musculo-esquelética (75); análisis y creación de tácticas de juego (76). Son muchas las marcas que lanzan al mercado soluciones tecnológicas para los cometidos anteriores. Las nuevas tecnologías han de utilizarse con cautela ya que antes de usarlas de forma aplicada deben ser validadas previamente frente al gold estándar (77) para asegurar que los datos que proporcionan sean válidos y fiables.

Los sistemas ópticos de captura de movimiento (OS) son ampliamente utilizados en tenis y son el gold estándar para medir parámetros cinemáticos. De hecho, estos sistemas tienen un error de medición inferior a 0.5 mm en la mayoría de los casos (78) y son ampliamente utilizados en diversas aplicaciones, como animación, biomecánica, deportes, medicina, entretenimiento y simulación. Suelen incluir 3 componentes:

- Cámaras infrarrojas y de rango visible: Se colocan varias cámaras alrededor del área de interés para capturar el movimiento desde diferentes ángulos. Estas cámaras en la mayoría de los casos son de alta velocidad y alta resolución para obtener datos precisos.
- Marcadores reflectantes o dispositivos de seguimiento: Los sujetos u objetos que se monitorizan llevan marcadores reflectantes u otros dispositivos que son fácilmente detectables por las cámaras. Estos marcadores pueden ser colocados en puntos específicos del cuerpo o el objeto que se quiere rastrear.
- Software de análisis: la información capturada por las cámaras se procesa a través de un software especializado que reconstruye la posición tridimensional de los marcadores en tiempo real. Este software puede proporcionar datos detallados sobre el movimiento, como la velocidad, la aceleración, y los ángulos articulares en el caso de estudios biomecánicos.

A pesar de la alta precisión de los OS presentan una dificultad añadida para usarlos fuera de un laboratorio (79). En este punto, se vuelve necesaria la utilización de tecnologías con mayor portabilidad que nos permitan obtener datos en situaciones reales de juego (wearables) (80). Teniendo en cuenta lo anterior, la presente tesis se centrará en las de tecnologías portables o wearables, partiendo de su validación en caso de que aún no esté realizada y continuando a su aplicación en contextos ecológicos.

Una de las tecnologías wearables más utilizadas en tenis son las unidades de medida inercial (IMUs) (62, 63, 77). Los IMUs se utilizan para el análisis cinemático de los distintos golpes de tenis en situaciones reales de juego (81). Son pequeños dispositivos que se colocan en los segmentos corporales que estemos interesados en monitorizar y están compuestos de tres componentes: magnetómetro, acelerómetro y giróscopo. A partir de sus tres componentes pueden calcular aceleraciones (m/s^2), velocidades angulares (rad/s) e incluso angulaciones articulares en los tres ejes del espacio si se combinan varios IMUs (figura 5) mediante el uso de algoritmos de fusión de sensores (82). Algunas de las marcas fabricantes de IMUs con más prestigio científico son Xsens® (83) y Nexgen® (67) ya que se ha comprobado su validez y fiabilidad en tenis frente al gold estándar (OS). Una importante alternativa a ellos son los sensores NOTCH®, cuyo eso está menos extendido, pero cuentan con prestaciones similares o superiores y por un precio menor. Aunque los sensores NOTCH® constituyen una alternativa “low cost” respecto al resto de marcas del mercado, estos aun no tienen testada su validez y fiabilidad en tenis. En la presente tesis se hará uso tanto de los sensores Nexgen® como NOTCH®. Otro aspecto a tener en cuenta para usar los IMUs en análisis cinemáticos de tenis será la frecuencia de muestreo que sean capaces de alcanzar ya que el tenis es un deporte explosivo donde los segmentos corporales llegan a alcanzar los 2000 grados por segundo durante los momentos previos al impacto con la pelota (84).

La frecuencia de muestreo se puede definir como el número de muestras por segundo recogidas por un determinado sistema procedentes de una señal analógica continua (85). La frecuencia de muestreo ha sido una preocupación tradicional para los investigadores de ciencias del deporte (91, 92). Desde una perspectiva teórica, la tasa de muestreo óptima debería calcularse siguiendo el teorema de muestreo de Nyquist–Shannon, que establece que, en una conversión de analógico a digital, la frecuencia de muestreo mínima necesaria para evitar ambigüedades y pérdida de información en la reconstrucción de la señal analógica original es igual al doble de su frecuencia máxima (85).

Desde un punto de vista operativo, la frecuencia de muestreo suele seleccionarse mediante el uso de un sistema de referencia y evaluando el equilibrio de error de la señal en relación con las tasas de muestreo (93, 94). No existen estudios que analicen la influencia de la frecuencia de muestreo en la precisión de IMUs para medir variables cinemáticas, en el caso particular del tenis (66). En esta línea, algunos autores sugieren que una frecuencia de muestreo de 200 Hz es la recomendada para analizar la cinemática en golpes de tenis (90), pero este asunto no ha sido analizado en profundidad. De hecho, los estudios de validación de IMUs en tenis han utilizado una única frecuencia de muestreo, coincidiendo con el rango máximo de muestreo de los dispositivos evaluados. Por ejemplo, Pedro et al. (83) analizaron el sistema Xsens® MVN a 240 Hz, mientras que Delgado-García et al. (67) evaluaron el sistema Nexgen® Ergonomic a 128 Hz.

La aplicación de los IMUs no solo posibilita el análisis de la técnica de golpeo de los tenistas, sino que también contribuye a reducir el riesgo de lesiones musculo-esqueléticas al permitir la detección de acciones ineficientes en las articulaciones (91). La utilización de IMUs se revela como una herramienta integral para la evaluación biomecánica, ofreciendo indicadores valiosos que pueden ser fundamentales tanto para la mejora de la técnica como para la prevención de posibles lesiones. Este enfoque integral, centrado en la cinemática y la seguridad musculo-esquelética, destaca la versatilidad y utilidad de los IMUs en el contexto específico del tenis.

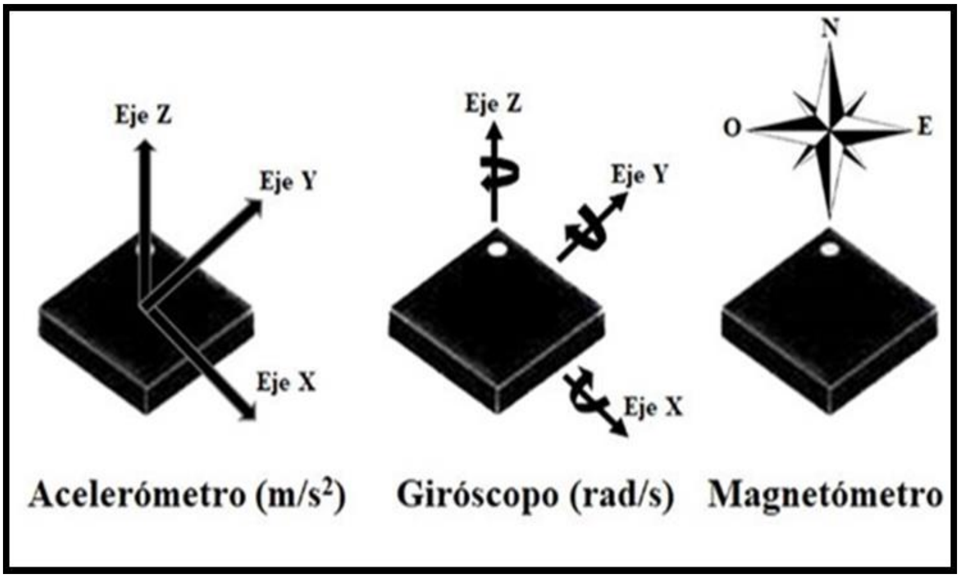


Figura 5. Representación de los tres componentes de un IMU, sus ejes de coordenadas y unidades de medida

Otro de los wearables más utilizados en tenis son los relojes deportivos dotados de fotopletismografía (PPG) (92). La PPG se basa en un sistema óptico no invasivo de medición de la frecuencia cardiaca mediante la detección de cambios del volumen sanguíneo en puntos periféricos del sistema cardiovascular (93). Este sistema está compuesto de dos componentes, una fuente de luz y fotorreceptor que recibe la luz reflejada detectando así los cambios de volumen en el torrente sanguíneo (figura 6). Al igual que los sensores inerciales, existen multitud de marcas que sacan al mercado este tipo de dispositivos (Xaomi®, Polar®, Suunto®, Garming®, etc.), pero no en todos se ha testado la validez y fiabilidad de los datos que aportan, por lo cual, se deberán llevar a cabo las validaciones pertinentes antes de utilizarlos de forma aplicada. Para ello, se medirá el grado de acuerdo de los datos que reportan con el gold estándar de medición de frecuencia cardiaca que en este caso serían los electrocardiogramas (ECG) (94). A pesar de que los ECG tienen testada su alta precisión presentan dificultad para utilizarlos en situaciones reales de juego como la mayoría de tecnologías no portables (94). Los sistemas PPG nos permiten monitorizar la frecuencia y variabilidad cardiaca en situaciones ecológicas, por lo tanto, pueden facilitar a entrenadores el control de la carga interna de sus tenistas tanto en competición como en los entrenamientos y así optimizar su programa de entrenamiento a lo largo de la temporada (95). En cambio, la principal desventaja de los sistemas PPG es que se ven afectados por los movimientos corporales e incluso por el tono de la piel (96) lo que hace aún más necesaria su validación antes de usarlos.

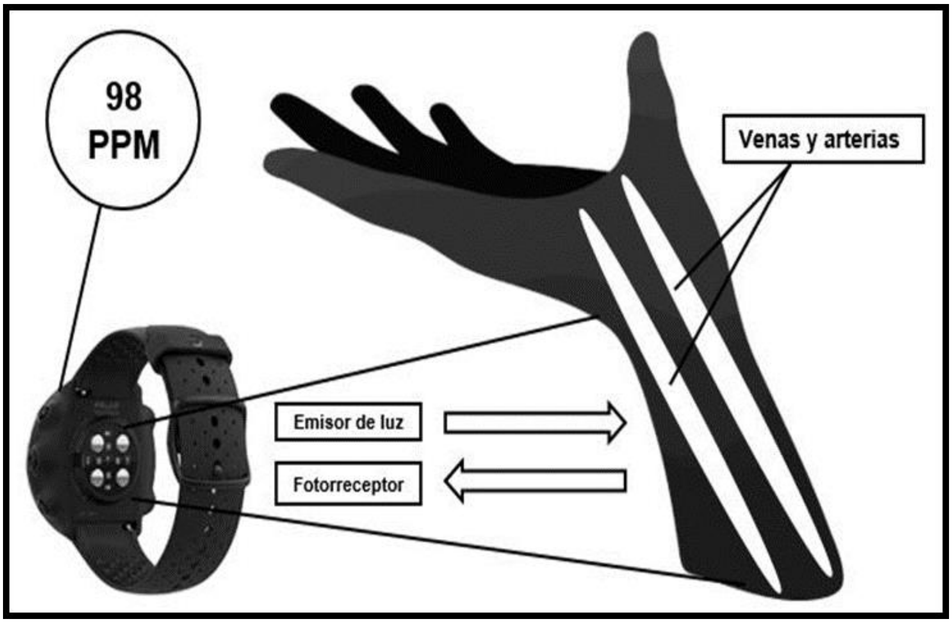


Figura 6. Representación del funcionamiento de un sistema fotoplestimográfico

Existen otras tecnologías que están influyendo en el tenis, que no se han utilizado de forma directa, pero que merece la pena comentar dada su relevancia:

- Raquetas y sensores inteligentes: existen raquetas y sensores que recopilan datos durante el juego. Estos dispositivos pueden medir variables como la velocidad de golpeo, el ángulo de impacto, efecto y fuerza aplicadas, identificación del tipo de golpe, entre otros parámetros. La información que recopilan sirve de ayuda a los jugadores y entrenadores a analizar y mejorar su rendimiento. Algunos ejemplos existen en el mercado son: Babolat Play®, Sony Smart Tennis Sensor®, Clipp®, Zepp Tennis® y Head Tennis Sensor®.

- Sistemas de rastreo de la pelota: Mediante el uso de cámaras y sistemas de seguimiento de movimiento, se puede realizar un seguimiento preciso de la trayectoria de la pelota durante el juego. Esto no solo ayuda en la toma de decisiones de los árbitros, sino que también proporciona datos valiosos para el análisis del juego (errores no forzados, winners, etc.). El ejemplo, en este caso, más conocido en tenis es el "Hawk-Eye", utilizado en la mayoría de tornes de la ATP.
- La realidad virtual y la realidad aumentada: la realidad virtual y la realidad aumentada se utilizan para crear experiencias inmersivas de entrenamiento (97). Los jugadores pueden practicar en entornos virtuales que replican situaciones de juego real, lo que les permite mejorar sus habilidades y reacciones en un entorno controlado. Un ejemplo del mercado es Virtual Reality Tennis® (VTR).
- Inteligencia artificial: Los sistemas de inteligencia artificial se utilizan para analizar patrones de juego, identificar áreas de mejora personalizadas y proporcionar recomendaciones específicas para un entrenamiento individualizado (98). Oracle® es un ejemplo de compañía que ha trabajo en conjunto con la ATP para desarrollar sistemas de inteligencia artificial que analizan datos y proporcionan

indicadores de utilidad para planificar el entrenamiento de los tenistas.

Las tecnologías anteriores están transformando la forma en que se juego y se entiende el tenis, proporcionando a los jugadores herramientas avanzadas para mejorar su rendimiento y ofreciendo a los aficionados experiencias más envolventes.

Como podemos observar la aplicación de la tecnología informática al deporte es cada vez más frecuente (99). Dicha aplicación incluye adquisición, modelado y análisis de datos computacional, computadores móviles y redes de la tecnología de la información (103, 104). Los asesores virtuales son un tutor que muestra ejemplos y realiza demostraciones, empleando: infografías 3D con actores sintéticos (avatar 3D); realidad aumentada; realidad virtual; proporciona biofeedback a tiempo real de indicadores de salud y rendimiento; gestiona alertas y avisos, en caso de consecución de hitos o bien cuando se superen umbrales; interacciona con los wearables; gestiona refuerzos positivos (102). Existen trabajos previos en la bibliografía que utilizan asistentes virtuales en deporte, como es el caso de aplicaciones utilizadas para optimizar el rendimiento en rugby, boxeo, kárate y balonmano (102–104) pero aún no existe ninguna solución en el mercado de aplicaciones que lo haga en tenis.

Las antiguas limitaciones de hardware y software, obligaban a los entrenadores a utilizar el método tradicional de análisis de video para analizar la técnica y tácticas de sus jugadores. Sin embargo, el análisis de video está muy limitado por la perspectiva de la cámara durante la grabación, lo cual impide la interactividad, algo extremadamente importante si se necesita recoger los momentos claves dentro de un gesto técnico concreto, por ejemplo (102). Además, el análisis de video solo permite analizar acciones que tuvieron lugar en un tiempo determinado. Las mejoras de la tecnología y la potencia de procesamiento permiten que los asesores virtuales superen las anteriores limitaciones al proporcionar demostraciones a tiempo real y entornos inmersivos e interactivos (102).

Lo desarrollado en el párrafo anterior, supone la justificación del desarrollo de una aplicación basada en asesores virtuales, enfocada en el aprendizaje integral del tenis. Debido a que presenta múltiples ventajas respecto a los tradicionales análisis de video convencional. Dicha aplicación aprovecha las funcionalidades de los asesores virtuales como una solución innovadora para mejorar la técnica y las tácticas en el tenis, ofreciendo una experiencia de aprendizaje integral (biomecánica, fisiología y psicología) que aborda las demandas específicas de este deporte de manera más efectiva (102).

OBJETIVOS

2. OBJETIVOS

El objetivo general de la presente tesis doctoral fue analizar la eficacia del empleo de tecnologías portables para la monitorización de indicadores de rendimiento y salud en tenistas, mediante la medición de variables biomecánicas y fisiológicas en situaciones reales de juego e incluyendo participantes de todos los niveles de juego durante la práctica del tenis.

Para la consecución del anterior objetivo general se proponen los siguientes objetivos específicos, desde un enfoque multidisciplinar, que permita la creación de una aplicación de evaluación integral del tenista, basada en el uso de asesores virtuales.

2.1. OBJETIVOS ESPECÍFICOS

Los dos siguientes objetivos específicos se centraron en la validación de tecnologías wearables útiles para la evaluación biomecánica y fisiológica del tenista:

- Analizar la validez concurrente del sistema PPG Polar Precision Prime® midiendo la frecuencia cardiaca durante una sesión de entrenamiento de tenis (*estudio 1*).
- Examinar la validez y fiabilidad de los IMUs NOTCH® para medir angulaciones de codo durante derecha de tenis a diferentes frecuencias de muestreo (100 Hz, 250 Hz y 500 Hz) (*estudio 2*).

Una vez evaluada la validez y fiabilidad de los sistemas wearables, se continuó con su aplicación en situaciones reales de juego con el objetivo de obtener conclusiones de valor para el ámbito científico de la biomecánica:

- Comparar la cinemática angular y la CI de miembros superiores entre el revés a una y dos manos de tenis en una muestra de jugadores de competición mediante el uso de giróscopos. Además de comparar las velocidades de pelota y precisión obtenidas por ambos tipos de revés (*estudio 3*).
- Analizar la variabilidad motora intrasujeto de los principales golpes de tenis (es decir, golpes de fondo y saque) en función del nivel de juego y el segmento corporal implicado (*estudio 4*).

Teniendo en cuenta los resultados y conclusiones de todos los objetivos específicos anteriores se pasó a realizar el desarrollo tecnológico:

- Desarrollar e implementar un asesor virtual de tenis en un entorno Android®, aportándole toda la experiencia previa de los estudios.

Finalmente, para la consecución de los objetivos anteriores se plantean los siguientes objetivos transversales.

2.2. OBJETIVOS TRANSVERSALES

- Crear un protocolo de evaluación de tenistas basado en un test de golpeo en pista que incluya la monitorización mediante wearables para el desarrollo de los estudios 3 y 4.
- Crear una base de datos de referencia que incluya aspectos biomecánicos y fisiológicos con los estudios desarrollados para su posterior inclusión en la aplicación basada en el entrenador virtual de tenis. Con el objetivo de que el asesor pueda detectar en un futuro indicadores de rendimiento y salud de gran utilidad para entrenadores y científicos

CONSIDERACIONES METODOLÓGICAS GENERALES

3. CONSIDERACIONES METODOLÓGICAS GENERALES

3.1. PARTICIPANTES Y PROCEDIMIENTOS

La muestra total de tenistas medidos en el presente trabajo fue de 110 (102 hombres y 8 mujeres) repartidos en los distintos estudios (tabla 1). En todos los estudios se utilizó el *International tennis number* para establecer el nivel de juego de los jugadores (105). Dicha clasificación ordena en una escala del 1 al 10 a los jugadores, existiendo 5 categorías: 1 jugadores profesionales que participan en torneos de la ITF; 2-4 tenistas de nivel avanzado que participan en competiciones regionales; 5-6 jugadores de nivel intermedio que practican tenis al menos dos veces por semana; 7-8 tenistas de nivel intermedio que juegan a tenis al menos dos veces al mes; 9-10 jugadores que acaban de iniciarse en la práctica del tenis. Para conocer más detalles sobre el *International Tennis Number* se debe visitar la página oficial de la ITF: https://worldtennisnumber.com/eng/your-number. En los casos en los que la composición corporal de los participantes fue de interés se medió mediante bioimpedancia (*estudios 1-4*) (Inbody 230®, Inbody, Seoul, Korea). El cual reportaba de forma automática un informe de composición corporal que se entregó a los sujetos evaluados en los distintos estudios de la presente tesis (*anexo 5*) a modo de reclamo y compensación.

Tabla 1. Distribución de los participantes en los distintos estudios de la presente tesis y clasificación por género, lugar de realización y nivel de los jugadores

Estudios	Muestra	Género		Zona de realización	Nivel*
		Masculino	Femenino		
Estudio 1	40	32	8	Pista de tenis	Todos
Estudio 2	15	15	0	Laboratorio	Campetición
Estudio 3	20	20	0	Test de golpeo en pista	Competición
Estudio 4	34	34	0	Test de golpeo en pista	Intermedio
Desarrollo tecnológico	1	1	0	Laboratorio	Competición

Los participantes fueron informados sobre los objetivos de la investigación en cada caso y firmaron un consentimiento informado (anexo 1) antes de realizar cualquier tipo de prueba. Se informo a los participantes que podían renunciar a su intervención en cualquier momento. Los tenistas fueron tratados según las directrices de la Asociación Estadounidense de Psicología (APA) que garantizaba el anonimáto de todas sus respuestas. Además, todos los estudios se realizarón siguiendo los principios éticos de la Declaración de Helsenki para investigación con humanos y fueron aprobados por el comité de ética de la Universidad de Granada (Ref. 912/CEIH/2019) (*anexos 2 y 4*). Los criterios comunes de inclusión de la muestra fueron: i) reportar una visión normal y no tener antecedentes de deterioro neuropsicológico que pudiese afectar al resultados de los estudios, (ii) no haber sufrido ningún tipo de lesión en los dos meses previos a la realización del estudio, (iii) no haber realizado actividad física intensa en las 48 horas previas a la participación en la investigación y (iv) firmar el consentimiento informado.

Durante las tomas de datos de la presente tesis los tenistas siempre utilizaron su propia raqueta. Se llevó a cabo una revisión de las raquetas utilizadas por cada participante para garantizar que estuviesen en buen estado en función de las directrices de la ITF (106). En cuanto a las pelotas, siempre se utilizó el mismo modelo (Wilson Pro Trainer, Wilson Sporting Goods, Chicago, United States), siendo cambiadas por otras nuevas cada 5 participantes evaluados. Los estudios donde se realizó test de golpeo en pista *(estudios 3 y 4),* se adaptó el Loughborough Tennis Test (107) en función de las necesidades específicas del estudio (figura 7).

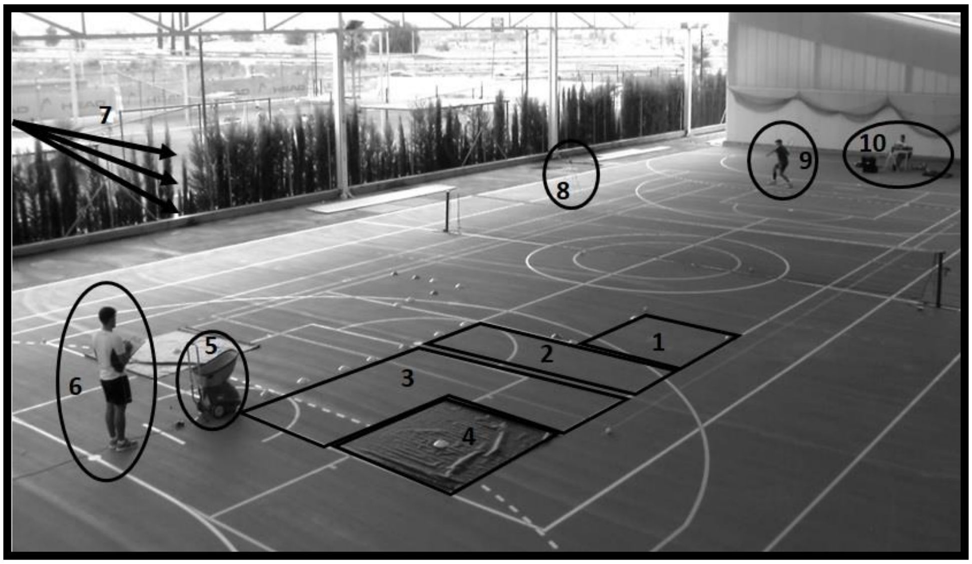


Figura 7. Test de golpeo realizado para los estudios 4 y 5. *1: Diana de saque; 2: zona de precisión baja de golpes de fondo; 3: zona de precisión media de golpes de fondo; 4: Zona de precisión máxima de golpes de fondo; 5: máquina lanza-pelotas; 6: investigador; 7: Cámara cenital registrando el bote de la pelota; 8: Cámara GoPro sincronizada con los IMUs colocados al jugador; 9: jugador golpeando; 10: investigador

En la tabla 2 se pueden observar las distintas variables, estudios donde se utilizaron, su unidad de medida y sistema de obtención del presente trabajo.

Tabla 2. Variables, unidades de medida y sistema de obtención de la presente tesis

Variable	Unidad de medida	Estudio	Sistema
Frecuencia cardiaca	Pulsaciones por minuto (PPM)	Estudio 1	Reloj deportivo y banda pectoral
Velocidad angular (ω)	Rad/s	Estudios 2, 3 y 4	Sensores inerciales
Pico de velocidad angular (ω_{peak})	Rad/s	Estudio 3 y 4	Sensores inerciales
Velocidad angular resultante (Rω)	Rad/s	Estudios 3 y 4	Sensores inerciales
Coordinación intersegmentaria	Distancia en nº de muestras al ω_{peak} del antebrazo	Estudio 3	Sensores inerciales
Angulaciones articulares	Grados (°)	Estudio 2	Sensores inercial y sistema 3D
Velocidad de la pelota	Km/h	Estudios 3 y 4	Radar de velocidad
Precisión de golpeo	% respecto al total	Estudios 3 y 4	Registro del bote de la pelota
Variabilidad motora	CV (%) de los ω_{peak}	Estudio 4	Sensores inerciales

*Véase la sección de resultados para mayor detalle de cada variable utilizada

3.2. INFRAESTRUCTURAS Y TECNOLOGÍAS UTILIZADAS

La presente tesis doctoral se llevó a cabo dentro del grupo de investigación CTS-545 "Human and Motion Lab" (https://www.humanlabugr.com/). El grupo CTS-545 tiene sus dos laboratorios (Human Lab y Motion Lab) repartidos en dos sedes, una principal, el Human Lab, ubicada en el Instituto Mixto Universitario de Deporte y Salud (iMUDS) y otra secundaria, Motion Lab, localizada en el edificio de servicios generales de la Facultad de ciencias de la salud (a escasos 500 m de la sede principal). Tanto Human como Motion Lab cuentan con instalaciones y tecnologías de evaluación biomecánica y fisiológica del deportista punteras a nivel nacional.

El iMUDS es una institución multidisciplinar de transferencia que cuenta con diversas unidades de investigación en actividad física y salud. Además, cuenta con una pista de tenis indoor reglamentaria de tipo A (106), donde se llevaron a cabo la mayoría de tomas de datos de la presente tesis, exceptuando aquellas que requerían de un laboratorio provisto de tecnologías no portables (*véase la sección de resultados para ampliar la información metodológica específica de cada estudio).*

3.2.1. Human Lab

En Human Lab se utilizó su zona de captura de movimiento 3D (*estudio 2*) equipada con el OS Qualisys® (Qualisys®, Gothenburg, Sweden) (Figura 8). Dicho sistema está compuesto por 9 cámaras infrarrojas de alta velocidad (Oqus 300, Qualisys, Sweden) y su software de procesado Qualisys Track Manager (versión 2.17, Qualisys, Gothenburg, Sweden). El OS Qualisys®

alcanza una frecuencia de muestreo de 500 Hz y se considera uno de los gold estándar para captura de movimiento 3D (108–110).

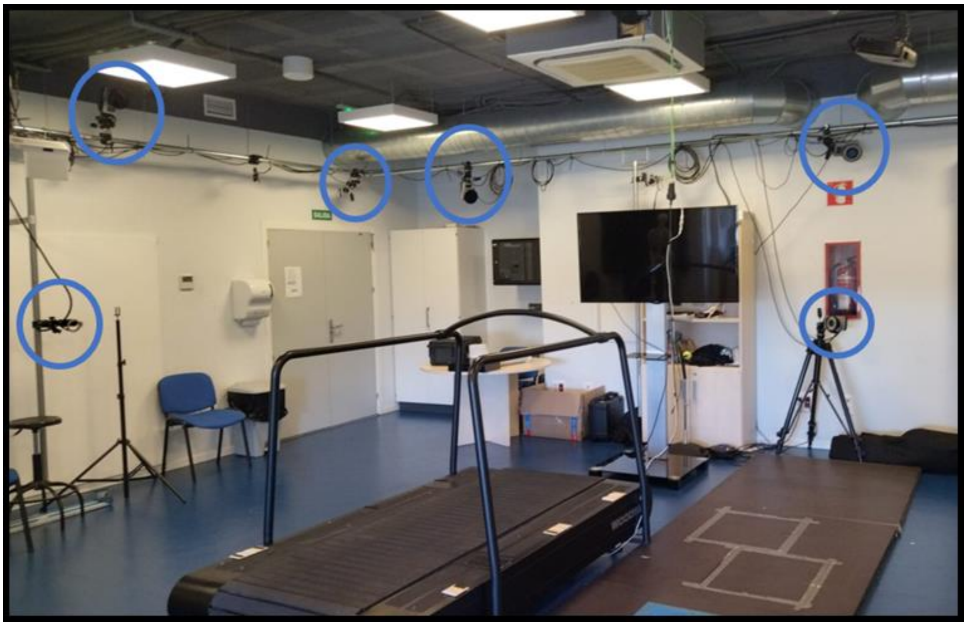


Figura 8. Zona de captura de movimiento (Qualisys®) del Human Lab

3.2.2. Motion Lab

El Motion Lab se utilizó durante la fase final de elaboración de la presente tesis *(desarrollo e implementación de un asesor virtual de tenis en aplicación Android).* Estas instalaciones cuentan con una zona de captura de movimiento 3D equipada con el OS OptiTrack® compuesto de 24 cámaras infrarrojas de alta velocidad (figura 9) y su software de procesado Motive 3.1. Dicho sistema, también se considera gold estándar de captura de movimiento 3D (111).

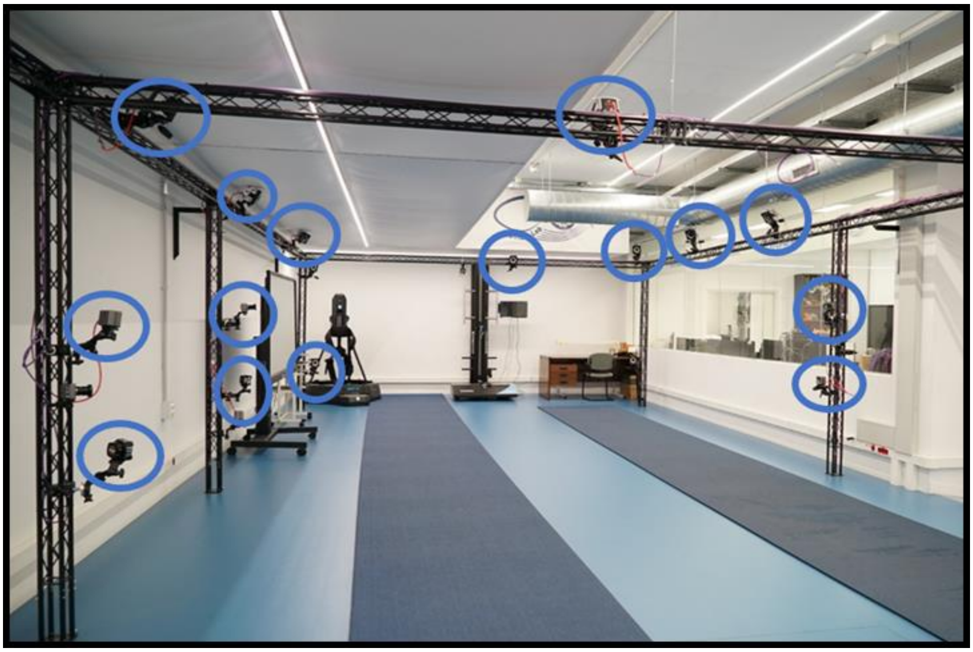


Figura 9. Zona de captura de movimiento (OptiTrack®) del Motion Lab

Todo el proceso de creación e implementación del asesor virtual de tenis se realizó en las instalaciones del Motion Lab mediante el siguiente procedimiento: se capturó al modelo humano que posteriormente sería el avatar mediante el escáner de luz estructurada ArtecEVA® (figura 10). A continuación, se pasó al procesamiento del asesor virtual mediante el software Artec Estudio Profesional 13®, que aportó la maya, textura y geometría. Los pequeños detalles del modelo (barba, pelo, manos, etc.) se refinaron y aplicaron con el software Zbrush 2r8®. Finalmente, se le realizó el rigging y skinning mediante el software Autodesk 3DS MAX®, con el cual el avatar quedó preparado para su implementación.

Figura 10. Proceso de escaneo del modelo para la creación del asesor virtual mediante escáner de luz estructurada ArtecEVA®

Una vez se tuvo lista la imagen del asesor virtual, se pasó a realizar las capturas de movimiento haciendo uso del OS OptiTrack®. Dichas capturas compondrían los futuros movimientos del asesor realizados por un jugador de nivel competición. Se utilizó un modelo de 50 marcadores, 2 clusters (manos) y se introdujo un elemento rígido (7 marcadores) para crear la raqueta del jugador (figura 11). Una vez se calibró el sistema (valores residuales de las cámaras inferiores a 0.4 mm) y se colocó el traje y los marcadores al actor, se continuó con la realización de las capturas. Se capturaron los principales golpeos de tenis: derecha, revés a una y dos manos, saque cortado, liftado y plano, cortado de derecha y revés y, por último, la volea tanto de revés como de derecha. Posteriormente, se exportaron los gestos técnicos mediante el software Motive 3.1. en formato .FBX. Los ficheros .FBX se insertaron en el asesor dotándolo de la capacidad de ejemplificar los principales golpes de tenis.

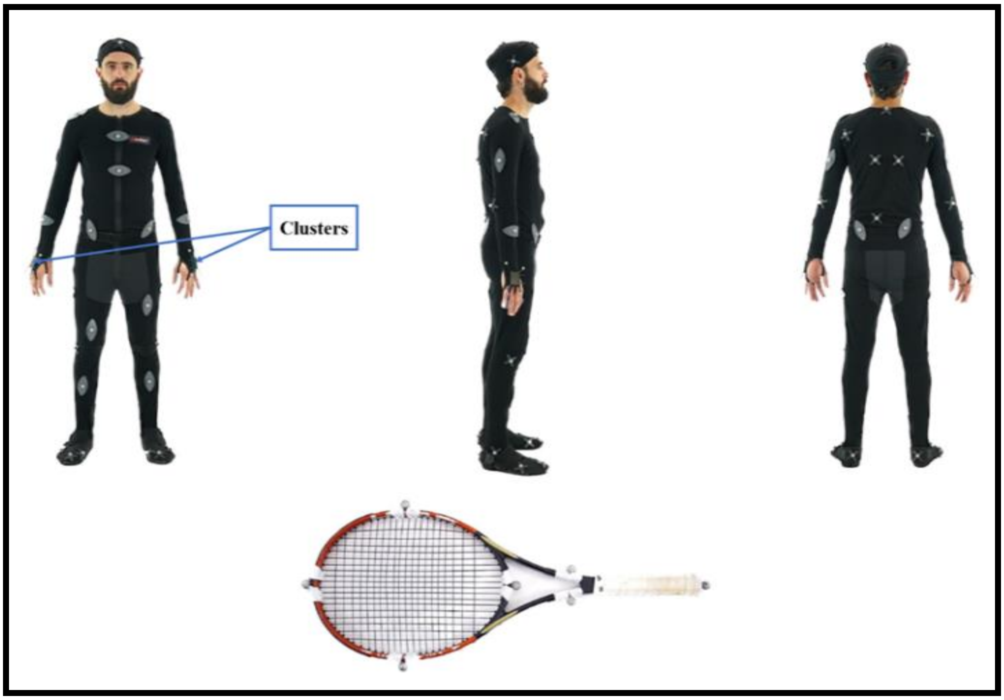


Figura 11. Modelo de marcadores y elemento rígido utilizados para realizar las capturas de movimiento 3D

Por último, se realizó la implementación del asesor virtual en un entorno Android, donde se incorporaron las siguientes funcionalidades: inserción del entorno (pista de tenis reglamentaria y pelota), ejemplificación de los distintos golpeos de tenis mediante selección, la posibilidad de rotar la cámara para centrarse en momentos concretos de la realización técnica y planificación del entrenamiento de la condición física del tenista mediante sesiones de ejercicio ya creadas. El desarrollo de la aplicación se realizó con el Software Unity®.

3.2.3. Pista indoor reglamentaria de iMUDS

En la pista de tenis del iMUDS (figura 12) se llevaron a cabo el resto de tomas de datos de la presente tesis (*estudios 1, 3 y 4*) ya que requerían de situaciones reales de juego y de la utilización de tecnologías portables o wearables (IMUs, radar de velocidad, máquina lanza-pelotas, relojes deportivos y cámaras GoPro®). Las tecnologías portables utilizadas se describen con mayor detalle a continuación:

Figura 12. Pista de tenis indoor reglamentaria (tipo A) del iMUDS

- Sensores inerciales Nexgen® Ergonomics I2M (128 Hz).
- Sensores inerciales NOTCH® (Wearnotch, Notch Interfaces, Inc., New Jersey, USA). Con una frecuencia de muestreo máxima de 500 Hz.
- Radar de velocidad Stalker Pro II®, Stalker Radar, USA.
- Máquina lanzapelotas Lobster Gram Slam 4®, California, USA.
- Reloj deportivo Polar Ignite®.
- Reloj deportivo Polar V800® sincronizado con banda pectoral H10®.
- Cámara GoPro Hero 4®.
- Cámara Panasonic HC-V160EC-K® (Panasonic, Japan).

3.3. ANÁLISIS ESTADÍSTICOS

Los análisis estadísticos utilizados en la presente tesis se realizaron en función de los objetivos concretos de cada estudio (*véase la sección de resultados*). Los softwares utilizados para la elaboración de todas las tablas, figuras, bases de datos y procesos estadísticos fueron los siguientes:

- IBM SPSS Statistic 20 (Chicago, IL).
- Software de análisis estadístico R®.
- OriginLab 9 Northampton, (MA).
- Microsoft Excel 2017.
- Matlab v. 2015.
- Extensión de excel Real Statistic Using Excel tool (112).
- Extensión de Excel Biomechanics Toolbar (113).
- Software libre Psychometric (114).
- Visual 3D software (C-Motion Inc., Germantown, MD)

4. RESULTADOS: ESTUDIOS DESARROLLADOS

ESTUDIO 1: CONCURRENT VALIDITY OF THE POLAR PRECISION PRIME® PHOTOPLETHYSMOGRAPHIC SYSTEM TO MEASURE HEART RATE DURING A TENNIS TRAINING SESSION.

4.1. ESTUDIO 1: CONCURRENT VALIDITY OF THE POLAR PRECISION PRIME® PHOTOPLETHYSMOGRAPHIC SYSTEM TO MEASURE HEART RATE DURING A TENNIS TRAINING SESSION.

Este estudio ha sido publicado en la revista *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, en el año 2023. Sus autores fueron: Emilio J. Ruiz-Malagón; Santiago Castro-Infantes; Maximiliano Ritacco-Real; Víctor M. Soto-Hermoso.

4.1.1. Resumen

Monitorizar la frecuencia cardíaca siempre ha sido importante para entrenadores y deportistas. Se presupone que los sistemas fotoplestimográfico (PPG) son menos eficaces midiendo frecuencia cardíaca en actividades con mucho movimiento de las extremidades superiores, como el tenis. Así, el objetivo de este estudio fue determinar la validez concurrente del sistema Polar Precision Prime® (PPP®) existente en el reloj deportivo Polar Ignite®. Las mediciones de frecuencia cardiaca media se realizaron durante una sesión de entrenamiento de tenis, dividida en tres partes (calentamiento, parte principal y vuelta a la calma) y un intervalo de 10 segundos. Se compararon los datos con la banda pectoral Polar H-10® sincronizada con el reloj deportivo Polar V800® (sistema de referencia). En el estudio participaron un grupo de 40 tenistas (32 hombres y ocho mujeres). Se obtuvieron valores medios, las diferencias entre sistemas y el error porcentual absoluto medio (MAPE) (< 4.04 ppm; < 5.03 %), reportándose pequeñas diferencias en todas las partes de la sesión y en el intervalo de 10 s. El sistema PPP® demostró una alta correlación (r> 0.89) y un ICC excelente (ICC > 0.96) en todas las partes de la sesión excepto en el intervalo de 10 s donde el ICC fue bueno (0.85). El error sistemático y el error aleatorio durante el calentamiento y el intervalo de 10 segundos fueron mayores (-0.99 ± 6.02 ppm y -2.41 ± 5.86 ppm, respectivamente) que la parte principal y la vuelta a la calma (-0.51 ± 1.16 ppm y -0.44 ± 4.02 ppm, respectivamente). Los resultados sugieren que la precisión del sistema PPP® no se altera a pesar de los movimientos de las extremidades superiores durante sesiones de entrenamiento de tenis de una hora. En conclusión, el sistema Polar Ignite® PPG es una herramienta válida para monitorizar la frecuencia cardíaca durante una sesión de entrenamiento de tenis.

Palabras clave: reloj deportivo Polar Ignite®; muñeca; jugador de tenis; deportes de raqueta; dispositivo vestible; monitorización de la frecuencia cardiaca.

4.1.2. Abstract

Monitoring heart rates has always been important for coaches and athletes. Photopletismographic systems (PPG) are supposed to be less capable of determining heart rate measure in activities with high upper limb movement, such as tennis. Thus, the aim of this study was to determine the concurrent validity of the Polar Precision Prime® (PPP®) system existing in the Polar Ignite® sports watch. This was accomplished by measuring averaged heart rates during a tennis training session, divided in three parts (warm-up, main-part and cool-down) and averaged per 10s-intervals by comparing data with the Polar H-10® chest strap synchronised with the Polar V800® (criterion measure). A group of 40 tennis players (32 males, eight females) took part in the study. Mean average values and between-systems differences and Mean Absolute Percentage Error (MAPE) were obtained (< 4.04 bpm; < 5.03 %), reporting small differences in all session parts and 10s-intervals. The PPP®

system reported high correlation (r> 0.89) and excellent ICC (ICC > 0.96) in all session parts except the 10s-intervals where the ICC were good (0.85). The systematic bias and random error during the warm-up and 10s-intervals were greater (-0.99 ± 6.02 bpm and -2.41 ± 5.86 bpm, respectively) than the main-part and cool-down (-0.51 ± 1.16 bpm and -0.44 ± 4.02 bpm, respectively). Results suggest that the PPP® system precision is not altered despite upper limb movements during one-hour tennis training sessions. In conclusion, the Polar Ignite® PPG system is a valid tool for monitoring heart rate during a tennis training session.

Palabras clave: Polar Ignite®, multisport watch, wrist, tennis players, racket sports, wearable devices, heart rate monitoring.

4.1.3. Introduction

Resting and exercise-related heart rate (HR) measurements have received special interest in recent years and are considered potentially useful within multivariate response monitoring, because they supply non-invasive and time-efficient understanding about the status of the autonomic nervous system and aerobic fitness. A comprehensive monitoring of fitness, fatigue, and performance is essential for understanding an athlete’s individual responses to training to optimize the strategy of scheduling training and recovery (95).

Nowadays, traditional chest straps are giving way to a new method of measuring HR called PPG. PPG is a non-invasive optical technique widely used for studying and monitoring the pulsations associated with changes in blood volume in a peripheral vascular bed (83, 139, 140). The system is composed by two components: a light source and a photodetector that receives the light that has been reflected, detecting the differences in fluid volume. As the heart beats, volume changes. A high blood volume causes less light to return to the optical sensor, whereas a low volume increases the amount of returning light (116). Over the past few decades, there has been a plethora of research in the field of PPG with potential applications beyond pulse oximetry, especially with the recent explosive growth of wearable technologies utilizing the technique of PPG (117). Optical HR acquisition from PPG sensors is known to be challenging (96). Indeed, one of the main challenges is the range of severe interference effects caused by movement (118).

ECG are the gold standard for measuring HR and are widely used in sport sciences (94). Despite the fact that ECG are an accurate tool to analyse HR, they are difficult to use outside the laboratory. For this reason, validation of more portable systems, such as PPG, is necessary to accurately evaluate an athlete's activities (94). PPG systems are a portable, easy to use and low-cost alternative to the ECG. It is, therefore, desirable that improvements in PPG HR estimation accuracy can be achieved (119).

Previous studies (120–122) analysed the concurrent validity of the Polar H-10® chest strap synchronised with the Polar V800® (Polar Electro, Kempele, Finland) compared to the gold standard ECG, noting that the Polar H-10® is a valid tool to analyse HR frequency in an endurance exercise.

This work is focused on the PPG multisport watch called the Polar Ignite® and its accuracy to measure HR during a tennis training protocol. This device has a new PPG system called Polar Precision Prime® (PPP), which solves the biggest problem of wrist optical HR monitors: inconsistent data from excessive movement (123) by combining the PPG system with a 3D accelerometer. Measuring the acceleration and the optical signal together enables the device to differentiate between volumetric changes caused by the pumping heart from the changes caused by the movement of the hand (124). Previous studies have analysed the validity of the Polar® PPG systems in other sports like running on a treadmill (125), high interval intensity training (126), swimming (127), sprint-based exercise (128) and at rest (129). All the previous studies concluded that PPP® is a valid tool to measure HR because it presents high levels of agreement with respect to the criterion measures. However, no validations of the Polar Ignite® were found during tennis practice and it has been shown that sports with more vigorous upper limb movements cause a significant increase in the error of the HR measurement with PPG systems. Tennis is a sport that involves high rotational velocities in the arm (arm internal rotations or wrist flexion movements) that sometimes exceed 2000 degrees per second (84).

For this reason, the aim of the current study was to determine the degree of agreement between the Polar H-10® chest strap synchronised with the Polar V800® (criterion measure) and Polar Ignite® when measuring HR during a tennis training session divided into three parts (warm-up, main-part and cool-down) and averaged per 10s-intervals. The authors hypothesised that Polar Ignite® would have a high level of agreement with Polar H-10® measuring averaged HR in 10s-intervals and all parts of the tennis training session.

4.1.4. Methods

Participants

A group of 40 healthy tennis players, eight women and 32 men, participated voluntarily in this study. According to the International Tennis Federation classification (105), all players could be categorized as advanced, having an international tennis number of between two and four (105). The anthropometric characteristics of the sample are presented in Table 3. All participants met the inclusion criteria: (1) to be a registered tennis player and (2) to have not suffered any injuries within the six-month period prior to the data collection. After receiving all the information about the study procedures, each participant signed an informed consent form, which complied with the ethical standards of the World Medical Association's Declaration of Helsinki (2013). The study was approved by the Institutional Review Board.

Table 3. Anthropometric characteristics of the participants

Variable	Participants (40)		Men (32)		Women (8)	
	Mean	SD	Mean	SD	Mean	SD
Weight (kg)	73.43	15.68	79.13	12.5	54.46	8.35
Height (cm)	173.93	11.12	179.12	3.02	156.66	10.96
SMM (kg)	32.26	6.52	35.36	2.71	21.96	3.93
BMI	24.12	3.83	24.73	4.18	22.1	1.15
BFP (%)	21.62	7.70	20.18	8.23	26.43	2.32

SD: Standard deviation; SMM: Skeletal muscle mass; BMI: Body mass Index; BFP: Body fat percentage

Procedures

Participants were individually tested within one day and were instructed not to perform any type of intense physical activity for at least 48 hours prior to the test. The test would be conducted at least three hours after eating. On the day of the study, participants could not take any medication that affected their HR. Participants wore their usual tennis training footwear and played with their own racquets to measure their typical performance. A one-hour tennis training session was performed (Table 4). The session lasted 60 minutes and it was divided into three parts: warm-up, main-part and cool-down. It included different rallies, volleys, serves and tie-breaks at different intensities. Participants were assigned partners from within the study sample in order to complete the tennis training session. They were matched considering their experience and level. One researcher supervised each session and controlled the duration and order of the training protocol.

Table 4. Description (in order of execution) and duration of each part of the tennis training session.

Part	Duration	Description
Warm-up	15´	Volley rally (forehand and backhand) Service line rally Baseline rally 10 services (5 each service box)
Main-part	40´	Baseline rally (higher intensity) Cross-court forehand rally Cross-court backhand rally Tie-break without serve Super tie-break with serve*
Cool-down	5´	Rest
Whole session	60´	

*depending on the super tie-break duration, players will play 1 or 2 in order to complete a one-hour training session

Material and testing

Anthropometric characteristics (weight [kg], height [cm], skeletal muscle mass [kg], Body Mass Index and body fat [%]) were measured using a bioimpedance meter (Inbody 230, Inbody Seoul, Korea) that has been validated previously by a system of dual-energy X-ray absorptiometry (130) and a precision stadiometer (SECA 222, SECA Corp., Hamburg, Germany).

Heart rate (bpm) was measured simultaneously with two different systems: The Polar H-10® chest strap synchronised with the Polar V800® (reference system with firmware version 3.1.1) previously used as gold standard (120) and the Polar Precision Prime® system, implemented in the

Polar Ignite® smartwatch (with firmware version 2.1.5). This sport watch measures HR peripherally via PPG. The training protocol lasted 60 min. The heartbeat recordings were exported from the Polar Flow website to an Excel spreadsheet after completing the tennis training session (two separate accounts were used for each participant to avoid possible cross-talk problems between devices). Both tools were easily synchronised considering that the Polar H-10® and Polar Ignite® systems recorded a HR value per second with given information related to the start time of each recording. Taking into account the manufacturer´s instructions, the Polar V800® was placed on the right wrist synchronised with the H10® chest strap. In contrast, the Polar Ignite® was placed on the left wrist. The devices were placed on each of the participants by the same researcher. A calibration time of 10-20 seconds was added, as stipulated in a previous study (125). The objective was to obtain the best HR monitor accuracy possible. The recording started right at the beginning of the tennis training session.

Statistical analysis

Descriptive statistics are represented as mean (standard deviation). The normal distribution of data and homogeneity of variances were confirmed through the Kolmogorov-Smirnov and Levene’s tests, respectively ($p>0.05$). To determine concurrent validity, Mean Absolute Percentage Error (MAPE) and Pearson correlation analysis were performed between the two devices (Polar Ignite® versus Polar H-10®) during a tennis training session divided into three parts (warm-up, main-part and cool-down) and averaged per 10s-intervals. The following criteria were adopted to interpret the magnitude of correlations between measurement variables: <0.1 (trivial), 0.1–0.3 (small), 0.3–0.5 (moderate), 0.5–0.7 (large), 0.7–0.9 (very large) and 0.9–1.0 (almost perfect) (131). Intraclass correlation coefficients (ICC) were also calculated between devices. Based on the characteristics of this experimental design and following the guidelines reported by Koo and Li (132), the authors decided to conduct a “two-way random average measures” model (ICC [2, k]), “mean of measurements” type, and “absolute” definition for the ICC measurement. The interpretation of the ICC was based on the benchmarks reported by a previous study (133): excellent, ≥ 0.90; good, 0.75–0.90; moderate, 0.60–0.75; and low, ≤ 0.60. The Bland-Altman (134) limits of agreement method was used to examine the systematic bias ± random error and the degree of agreement (95% limits of agreement) differences in HR between devices for each part of the tennis sessions and 10s-intervals. Heteroscedasticity of error was defined as an $r^2 > 0.1$ (135). The level of significance used was $p<0.05$. Data analysis was performed using the SPSS (version 21, SPSS Inc., Chicago, Illinois, USA), Excel 2016 and Real Statistic Using Excel Packages (112).

4.1.5. Results

Table 5 shows average values and between-systems differences in HR measured with Polar Ignite® and Polar H-10® during the different parts of the training session and 10s-intervals. Small differences were obtained between systems (< 4.04 bpm; < 5.03 %) in all session’s parts and 10s-intervals with a tendency to underestimate the HR by the Polar Ignite®. The 10s-intervals differences were the greatest (-4.04 bpm; 5.03 %) and cool-down differences were the smallest (-0.15 bpm; 0.11 %). Pearson correlation analysis reported almost perfect correlations ($r > 0.92$; $p < 0.05$) in warm-up (0.94; $p < 0.001$), main-part (0.99; $p < 0.001$) and cool-down (0.96; $p < 0.001$), in the case of 10s-intervals were very large (0.89; $p < 0.001$) (Table 5). ICCs between systems were also calculated (Table 5) reporting an excellent association (ICC > 0.96) in warm-up, main-part and cool-down, and good in 10s-intervals (0.85).

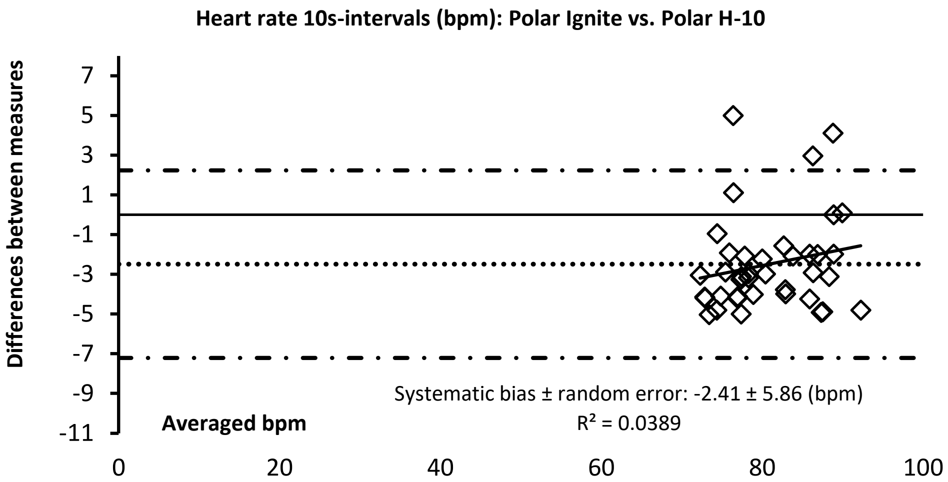
Table 5. Average values (standard deviation), between-systems differences, MAPE, Pearson (r) and ICC (Polar Ignite® vs. Polar H-10®) in HR (bpm) during the different parts of the tennis training session and 10s-interval

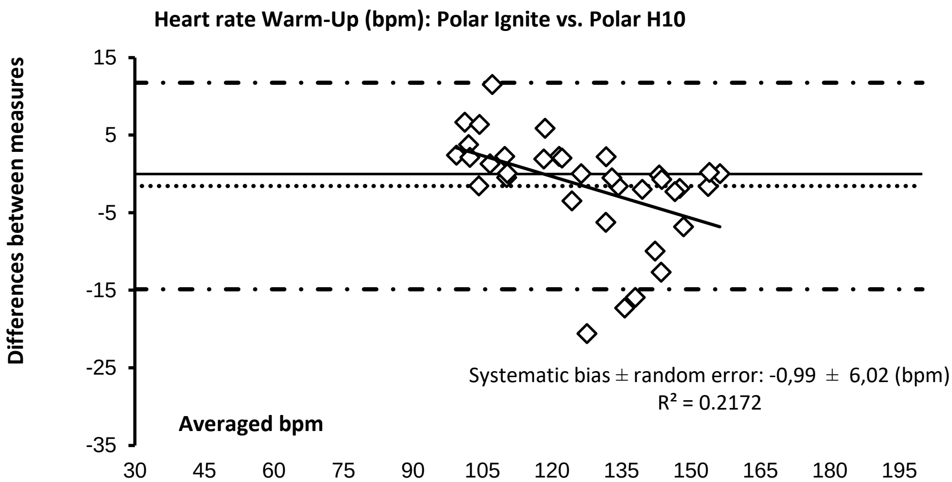
Variable	Part of the session	Polar Ignite® (bpm)	Polar H-10® (bpm)	Difference (bpm)	MAPE (%)*	Pearson (r)	ICC (95% CI*)
HR(bpm)	10s-interval	76.21 (11.25)	80.25 (16.49)	- 4.04	5.03	0.899***	0.857 (0.658-0.941)
	Warm-up	126.01 (16.17)	127.53 (19.25)	- 1.52	1.19	0.943***	0.962 (0.926-0.981)
	Main-part	141.67 (14.33)	141.93 (14.57)	- 0.26	0.18	0.994***	0.997 (0.994-0.999)
	Cool-down	125.98 (20.36)	126.12 (16.44)	- 0.15	0.11	0.929***	0.964 (0.921-0.984)

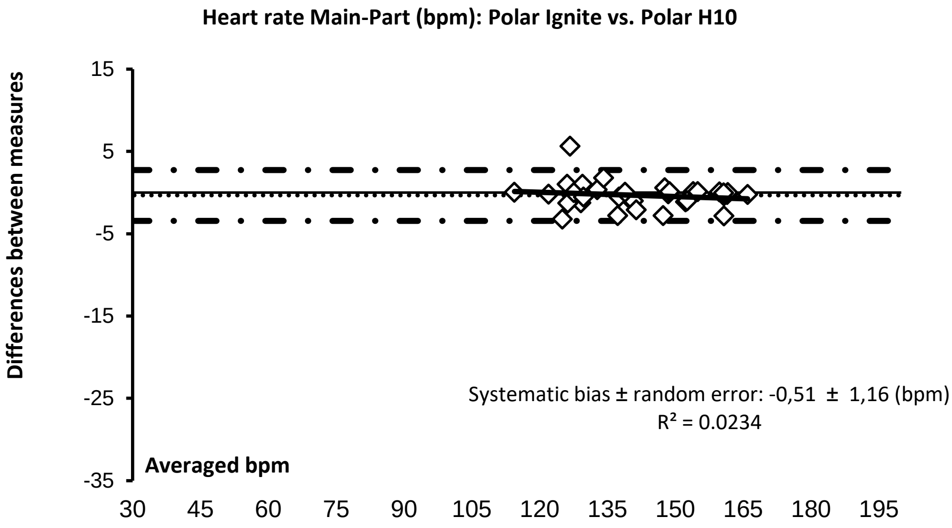
***indicates statistical significance for the Pearson correlation analysis ($p < 0.05$); * Confidence interval of 95 %.; *Mean Absolute Percentage Error

The Bland-Altman plots (Figure 13), shows the differences between the two systems in each part of the session and 10s-intervals. These plots exposed a small systematic bias: cool-down (-0.44 bpm) revealed less systematic bias than main-part, warm-up and 10s-intervals (-0.51 bpm; -0.99 bpm; -2.41 bpm, respectively). Instead, main-part showed smaller random error (± 1.16 bpm) than cool-down, 10s-intervals and warm-up (± 4.02 bpm; ± 5.86 bpm; ± 6.02

bpm, respectively). The differences between Polar H-10® and Polar Ignite® were heterocedasticity distributed in warm-up (r^2 = 0.2172). In contrast, 10s-intervals, main-part and cool-down differences were homocedasticity distributed (r^2 = 0.0389; r^2 = 0.0234; r^2 = 0.0352, respectively).







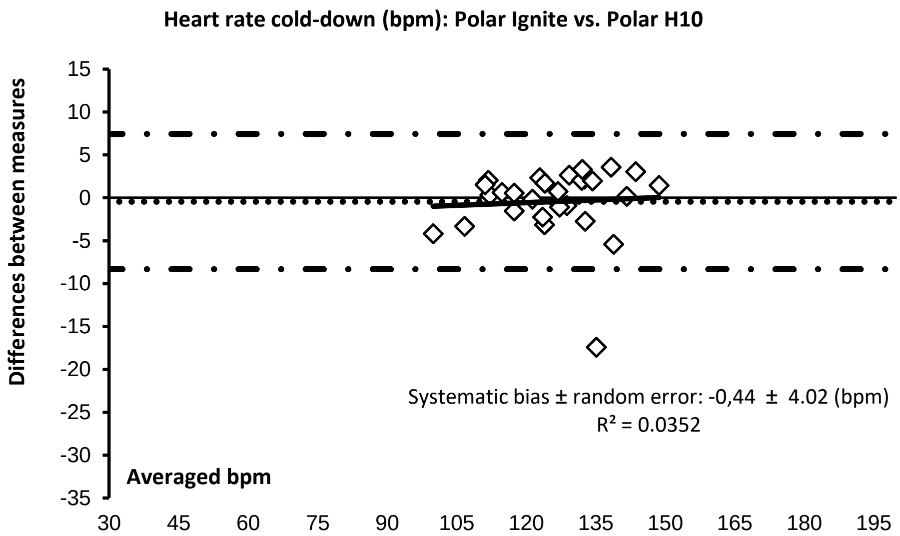


Figure 13. Bland-Altman plot with the heart rate (HR, in bpm) during tennis training session obtained from two different devices (Polar Ignite® and Polar H-10®). The plot includes the mean difference (dotted line) and 95% limits of agreement (dashed line), along with the regression line (solid line). Systematic bias and Pearson's multivariate coefficient of determination (r2) are also presented

4.1.6. Discussion

This study had the purpose of determining the concurrent validity of the Polar Ignite® PPG system for measuring HR during a complete tennis training session divided into three parts (warm-up, main-part and cool-down) and averaged per 10s-intervals, comparing the data against a Polar H-10® chest strap synchronised with the Polar V800® (criterion measure). Small differences were obtained between systems (< 4.04 bpm; < 5.03 %) in all session's parts and 10s-intervals with a tendency to underestimate the HR by the Polar Ignite®. The 10s-intervals differences were the greatest (-4.04 bpm; 5.03 %) and cool-down differences were the smallest (-0.15 bpm; 0.11 %). Data showed high correlations (r> 0.89) and excellent degree of agreement (ICC > 0.96) in all the comparisons made, except when investigating the data at the 10s-intervals where the ICC was good (ICC = 0.85). Bland-Altman plots revealed a small systematic bias and random error for all parts of tennis training sessions and 10s-intervals: 10s-intervals (-2.41 ± 5.86 bpm), warm-up (-0.99 ± 6.02 bpm), main-part (-0.51 ± 1.16 bpm) and cool-down (-0.44 ± 4.02 bpm).

In the present study, MAPE values obtained (10s-intervals: 5.03 %; warm-up: 1.19 %; main-part: 0.18 %; cool-down: 0.11 %) were similar to those of Nuuttila et al. (129) (1.1 %), where a Polar device with PPP® was also validated at rest. In addition, similar correlations values were shown in cycling (r > 0.79) (121), resistance training (r > 0.83) (121,136), stressful tasks (r > 0.90) (137), moderate physical activity (r > 0.80) (138) and at rest (r > 0.9) (129) in other Polar devices validations. The Polar Ignite® sport watch obtained a HR correlation of 0.83 with ECG (criterion measure) in a 12-minute running protocol at incremental speeds (138). Another study (139) measured resting

HR with a Polar watch (with PPP® system) reporting high correlations r = 0.9. A previous validation study of the PPP® system (125) during running on a treadmill, obtained average values and between-system differences (< 2.59 bpm) similar to those found in the present study (< -4.04 bpm; < 5.03 %) with longer recording periods (180s-intervals versus one hour of tennis training). Average values and between-system differences (125) manifested how the longer recording intervals time is increased, the lower differences are shown, which agrees with the results obtained in the average mean difference in our study in all sessions parts and 10s-intervals, confirming that the accuracy of the PPP® system is not altered during a tennis training session.

Following the previous studies (164, 165) it was obtained similar ICCs (> 0.98) during high intensity physical activities with the Polar OH1 and Polar RS800 optical HR sensors, reiterating the high accuracy of the PPP® system with long recording periods. Specifically, a recent study (92) measured the accuracy of another HR monitor (Polar OH1®) in tennis, obtaining an excellent degree of agreement (ICC= 0.995). Our study provides stronger information considering the total analysed minutes (508 vs ~ 2400 min) reporting a total ICC of 0.936. Referring the systematic bias and random error, in previous Polar OH1® validation studies (82, 166) obtained similar results (1.90 ± 2.39 bpm vs. -2.21 ± 5.62 bpm and 2.42 ± 1.49 bpm vs. -2.21 ± 5.62 bpm, respectively). Our systematic error and random error are considered small because when an athlete monitors HR for submaximal effort regulation, the limits of HR zones should be considered as a range rather than a point value (143). This range is established by Lamberts et al. (143) where they found a variation in HR of 1.1-1.4% for the same intensity. Therefore, differences of less than 1/2 bpm will not imply significant changes. Despite the abovementioned findings, perhaps the slightly higher level of agreement between the two devices obtained during the cool-down could be due to the lower amount of upper body movements during this part of the training (118).

Another study (144) declared that certain HR monitors (Apple Watch®, Fitbit Blaze®, Garmin Forerunner 235®, and TomTom Spark Cardio®) did not assess well (all $r < 0.76$) when using the elliptical trainer due to arm movements affect the accuracy of the devices. These results oppose ours ($r > 0.9$) because the short recording period (4.5 min) versus the one-hour tennis training protocol. These are not equivalent tasks (elliptical as opposed to tennis), but both involve upper limb movement so we suggest that differences could be decreased if we measure a long recording period. Therefore, Polar Ignite® PPG system could be an accurate HR monitor during tennis practice.

4.1.7. Conclusion

In conclusion, our hypothesis has been confirmed, the PPP® system existing in Polar Ignite® sports watch demonstrates a high level of agreement with the reference system Polar H-10®. Thus, it can be used as a valid measure of HR during all parts of the tennis training session (warm-up, main-part and cool down) and 10s-intervals.

From a practical standpoint, the results obtained in the current study reinforce the evidence regarding the validity of the Polar Ignite® Precision Prime system, which can be recommended to tennis players as an effective and reliable HR measurement system. Further, we found that the Polar Ignite® precision is not altered despite upper limb movements during a one-hour tennis training session, confirming it as a useful tool for fitness professionals, personal trainers, exercise physiologist and tennis coaches for controlling the physiological response and planning the season considering the training load of their tennis players even during competitive matches.

ESTUDIO 2: VALIDITY AND RELIABILITY OF NOTCH® INERTIAL SENSORS FOR MEASURING ELBOW JOINT ANGLE DURING TENNIS FOREHAND AT DIFFERENT SAMPLING FREQUENCIES.

4.2. ESTUDIO 2: VALIDITY AND RELIABILITY OF NOTCH® INERTIAL SENSORS FOR MEASURING ELBOW JOINT ANGLE DURING TENNIS FOREHAND AT DIFFERENT SAMPLING FREQUENCIES.

Este estudio ha sido publicado en la revista *Measurement,* en el año 2022, volumen 201. Sus autores fueron: Emilio J. Ruiz-Malagón; Gabriel Delgado-García; Santiago Castro-Infantes; Maximiliano Ritacco-Real; Víctor M. Soto-Hermoso.

4.2.1. Resumen

Los sistemas de captura de movimiento portátiles y de bajo costo están ganando importancia para el análisis biomecánico. El objetivo del estudio fue determinar la validez concurrente y confiabilidad de los sensores inerciales NOTCH® para medir angulaciones de codo durante el golpe de derecha en tenis a diferentes frecuencias de muestreo (100, 250 y 500 Hz), utilizando como referencia un sistema óptico de captura de movimiento con precisión submilimétrica. 15 jugadores competitivos realizaron golpes de derecha con los NOTCH colocados y un sistema de marcadores para la parte superior del cuerpo. Las señales de ambos sistemas fueron ajustadas y sincronizadas. La magnitud del error fue tolerable (5-10°) para todos los ejes articulares y frecuencias de muestreo, aumentando significativamente a 100 hercios para los ángulos de flexión-extensión y pronación-supinación ($p = 0.002$ y 0.023; Cohen $d > 0.8$). El coeficiente de correlación de concordancia fue muy fuerte (0.7–0.9) en todos los casos. La variación del error intrasujeto entre test-retest no mostró diferencias significativas ($p > 0.05$). En conclusión, NOTCH® es una alternativa válida, confiable y portátil para medir angulaciones de codo durante el golpe de derecha de tenis.

Palabras clave: IMU; captura de movimiento; cinemática articular en 3D; deportes de raqueta; fusión entre sensores.

4.2.2. Abstract

Portable and low-cost motion capture systems are gaining importance for biomechanical analysis. The aim was to determine the concurrent validity and reliability of the NOTCH® inertial sensors to measure the elbow angle during tennis forehand at different sampling frequencies (100, 250 and 500 hertz), using an optical capture system with sub-millimetre accuracy as a reference. 15 competitive players performed forehands wearing NOTCH and an upper body marker-set and the signals from both systems were adjusted and synchronized. The error magnitude was tolerable (5-10°) for all joint-axis and sampling frequencies, increasing significantly at 100 hertz for the flexion-extension and pronation-supination angles ($p = 0.002$ and 0.023; Cohen $d > 0.8$). Concordance correlation coefficient was very large (0.7–0.9) in all cases. The within-subject error variation between the test-retest did not show significant differences ($p > 0.05$). NOTCH® is a valid, reliable and portable alternative to measure elbow angles during tennis forehand.

Keywords: IMU; motion capture; 3D joint kinematics; racket sports; multi-sensor fusion

4.2.3. Introduction

Inertial measurement units (IMUs) are sensors used commonly in medical rehabilitation, performance and kinematics analysis in sports (169, 170). In tennis, the use of this type of technology has become increasingly frequent (147), since it is an economical and portable alternative that allows to estimate kinematic parameters such as the body segments' orientation, position and joint angles (148–150), the energy transition between segments during the strokes (151) or the ball speed based on a racket-mounted motion sensor (152). All this makes IMUs suitable to collect data in a natural environment and perform in-field tennis biomechanical analyses, which provide more valid results than laboratory tests (80).

OS are the gold standard for measuring kinematics parameters, and are widely used in sport sciences and tennis studies (39). In fact, these systems have been improved over the last two decades and the measurement error of current OS systems is less than 0.5 mm (78). Despite the fact that OS have been proven to be accurate tools to analyse sport kinematics (78), using them outside the laboratory is an added difficulty (79). The increase in costs and the complexity of the data processing reduce the extent of this approach in actual field applications. Thus, for example, to evaluate the hitting kinematics of a tennis forehand on an indoor tennis court (153), set up a system of 8 infrared cameras, which is not a viable solution for many research institutes. OS systems also involve precise and time-consuming marker placement. The simplest OS based model to assess elbow kinematics –which could be measured using only two IMUs, one on the arm and other on the forearm– are based on 5 reflective markers (177, 178). For this reason, validation of more portable systems, such as IMUs or wearable ultrawideband transceivers mounted on body segments (155), is necessary to be able to evaluate tennis players in real-game situations (80). Another alternative could be mocap markerless systems (156–158) but they still have the problem of complicated assembly and are difficult to use in conditions where player occlusion can occur.

IMUs usually contain three different types of sensors: magnetometer, accelerometer and gyroscope. Joint kinematics is computed by the use *sensor* *fusion algorithm,* combining accelerometer and magnetometer measurements with gyroscope measurements (82). From this, it follows that the algorithm will only work properly if all three sensors are capable of measuring the full range of accelerations and angular velocities (in the particular case of the accelerometer and gyroscope). This is not a concern in the case of slow-motion gestures such as walking or moving arms to bring an object but in ballistic and explosive skills, such as tennis strokes involving high rotational velocities, it could be a problem. The sensors have proven to be valid and reliable even in sports activities such as football (159) or swimming (160). These studies have established a good agreement and tolerable values for the root mean square error (between 5° and 10°) for measuring upper limbs kinematics, since the differences in the magnitude of the error can be attributed to biomechanical models and different calibration methods (161). Upper limbs angular velocities in tennis strokes – such as arm internal rotations or wrist flexion movements – sometimes exceed 2000 degrees per second (84), and most of the commercial sensors are limited to this range. For this reason, and especially in this case, sensors capable of capturing higher angular velocities are needed. Only two studies have been found that have evaluated the validity and reliability of the sensors in tennis strokes. One of them evaluates the accuracy of the gyroscopes (67), while the other evaluates the accuracy of the sensors Xsens® MVN system for measuring 3D joint angles (83). Xsens® MVN system proved to be valid to measure the kinematics of the arm for the majority of the variables analyses, but not for the elbow joint angle in transverse plane (83). There are also other recent studies that analyse the validity of an IMU system to measure the kinematics of ballistic gestures, but these works do not analyses the kinematics of the upper limbs, which is where the highest angular velocities are reached. For example, Harnett et al.,

(162) analyse the validity of some IMUs to study the kinematics of the knee, pelvis and trunk in the case of cricket and find no statistically significant differences with the reference system for the trunk lateral bending and knee flexion. The IMUs that has been proposed to be validated in this study (NOTCH®) only has only been previously validated during functional daily task movements (163). Despite previous validation studies, until now, there is scarce literature for the accuracy of the IMUs for measuring explosive upper limbs movements involving high rotational velocities and large ranges of movements, such as the tennis forehand.

The upper limbs kinematics of the tennis forehand is crucial to achieve high performance in tennis, as it contributes to achieve greater ball velocity (34, 188), ball spin (37) or higher stroke accuracy (39, 189). For example, Pedro et al. (150) conclude that the extension movement of the elbow is the second largest contributor to racket speed, after the horizontal flexion of the upper arm around the shoulder joint. Genovois et al., (37) indicate that during the backswing and forward swing of a topspin forehand, the forearm is more extended than during a flat forehand drive. In the impact and the follow-through, the elbow flexion and forearm pronation are also more pronounced in the topspin forehand drive (37). In the case of table tennis, inertial sensors allowed to differentiate the kinematics of the upper segments between able-bodied and wheelchair-bound players during forehand and backhand strokes (190, 191). In addition to improving the performance-related biomechanical factors, the implementation of these sensors for the upper limbs kinematics analysis could aid to assess the risk of musculoskeletal injury, considering that inefficient joint actions can increase the risk of injury (91). For example, there is a relation between hitting technique and elbow epicondylitis (166), a common tennis injury, and IMUs could serve to prevent the mechanical load on the elbow from being excessively high (167).

Sampling means taking a certain number of samples every second from a continuous analog signal (85). Sampling frequency (i.e. the amount of data collected per second) is something that has traditionally concerned researcher in the field (195, 196). From a theoretical overview, the optimal sample rate should be calculated following the Nyquist–Shannon sampling theorem which states that, under suitable assumptions, in an analog-to-digital conversion the minimum sampling frequency necessary to avoid ambiguity and loss of information (e.g., aliasing) in the reconstruction of the original analog signal is equal to twice its maximum frequency (85). From an operational point of view instrumental sampling frequency is usually selected by using a reference system and assessing the error trade-off of the signal in relation to the sampling rates (88,89). There are no studies that analyse the influence of the sampling frequency on the accuracy of the IMUs for measure kinematics variables in the particular case of tennis (66). In this vein, some authors suggest that 200 Hz is the recommended sampling rate needed to analyse the kinematics in tennis strokes (90), but this issue has not been analysed in depth. In fact, IMU validation studies in tennis have used a single sampling frequency, which coincide with the maximum sampling range of the devices evaluated. For example, Pedro et al., (83) analysed the Xsens® MVN system at 240 Hz or Delgado-García et al., (67) analysed the Nexgen® Ergonomic system at 128 Hz (Table 6). NOTCH® inertial sensors have not yet been evaluated, although their price and features make them ideal for use in tennis. In fact, some companies have already used them to design software to evaluate batting or swinging technique (4dmotionsports.com). If the researcher wants to make long-time recordings (such as a complete tennis match), it seems more convenient to use lower sampling frequencies so as not to saturate the memory of the devices and to be able to use popular mathematics software, limited from a computational point of view, such as Microsoft Excel. In other words, lower sampling rates would result in a lower data load, longer battery life, and higher efficiency of data processing (168). Similarly, it would be interesting to use higher sampling frequencies to see if the error decreases akin to other gestures of a ballistic nature (89). On this line low sampling frequencies could lead to missing peaks or spikes, a signal distortion and finally in a loss of information (89).

Table 6. Feature comparisons between NOTCH® and other IMUs presenting validation studies in tennis

	NOTCH®	Xsens® MVN	Nexgen® I2M
Reference of the validation study	-	[79]	[63]
Approximate cost of the system used in the study	<500 USD	>3.5K USD	>10K USD
Sampling frequency*1 (Hz)	500 Hz	240 Hz	128 Hz
Accelerometer maximum range (g)	± 32	± 16	± 6
Gyroscope maximum range (°/s)	± 4000	± 2000	± 2000
Magnetometer maximum range (Gauss)	± 16	± 8	± 6
Experimental conditions	-	Laboratory	Laboratory
Optical system used as reference criterion system	-	Qualisys AB	Optitrack (Natural Point)
Number of participants included	-	18	4
Level of expertise of participants	-	Experienced and intermediate	Beginner and competitive
Stroke analysed	-	Forehand	All
Number of strokes analysed per participant	-	3	100
Kinematic variable studied	-	Joint angle	Sensor angular velocity
Error reported relative to the reference (RMSE)	-	1.5-13.1 °/s	4.4-35.4 °/s
Reliability outcome	-	-	0.41-0.58 °/s*2

*1 Refers to the maximum sampling frequency (in the case of the Notch) or the one used in the validity study in the case of the IMU Xsens® MVN and Nexgen® I2M systems. *2 In this case, the reliability was studied by rotating the sensors on the same axis, not in tennis hits. RMSE: Root Mean Square Error

The aim was to determine the concurrent validity and reliability (within-subject error variation) of the NOTCH® inertial sensors to measure elbow joint angle during tennis forehand at different sampling frequencies (100 Hz, 250 Hz and 500 Hz), by comparing data with a OS (gold standard, 500 Hz) in a sample of competitive tennis players. Based on previous research, we hypothesise that NOTCH® is a low-cost and portable alternative (< $500 USD) that includes all instrumentation and data processing for measuring elbow joints angles in tennis forehand. Considering that there is a relationship between a proper technique and injuries, the confirmation of this hypothesis could help sport scientists measure upper limb kinematics and mechanical loads as well as prevent the appearance of tennis injuries, such as the tennis elbow, during field-based experimentation. Studying the validity and reliability of NOTCH® inertial sensors is also necessary to know if they are suitable for programming specific software for the evaluation of sport technique in the case of tennis.

4.2.4. Methods

Participants

Data were collected from 15 healthy players (all male) with experience in regional competitions. The anthropometric characteristics of the participants were as follows: mean (SD); age 22.4 (6.5) years; height 177.3 (5.5) cm; weight 75.4 (6.2) kg; BMI 21.1 (1.8) Kg/m^2. According to the ITF, 10 players had an international tennis number of between 2 and 3 (advanced tennis players), and five players had an international tennis number of 4 (105). All participants met the inclusion criteria: (1) to have the license form the National Tennis Federation and (2) to not suffer any injuries within the 6 months prior to the data collection. After receiving detailed information on the objectives and procedures of the study, each subject signed an informed consent form in order to participate, in compliance with the ethical standards of the World Medical Association's Declaration of Helsinki (2013). It was made clear that the participants were free to leave the study if they saw fit. The study was approved by the Institutional Review Board.

Procedures

Participants were individually tested within one day. First, the anthropometric characteristics (weight [kg], body fat [%] and height [cm]) were measured using a bioimpedance meter (Inbody 230, Inbody Seoul, Korea) and a precision stadiometer (SECA 222, SECA Corp., Hamburg, Germany). All measurements were taken with the participants wearing underwear.

Two IMUs and retroreflective markers (eight anatomical markers and two clusters) were affixed on the dominant arm of the tennis players (Figure 14), according to the University of Western Australia's upper body marker set with an extensive use in sport science and tennis studies (80, 199). Subsequently, the players performed the hitting test, using their own racket. They performed six series of 10 forehand recordings with the IMUs at 100 Hz, 250 Hz, and 500 Hz. Two series were recorded at each sampling frequency in order to analyse the reliability of the IMUs (within-subject error variation). The OS was recorded simultaneously at 500 Hz. All forehands performed in the study were carried out by hitting a pendulum ball (Figure 15).

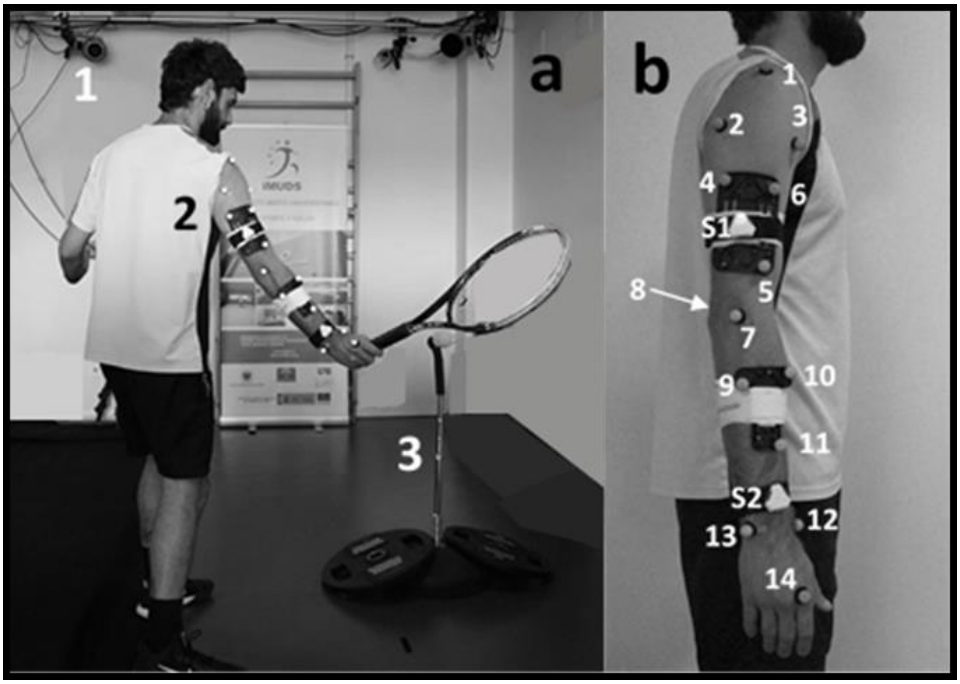


Figure 14. Set up of the experiment (a) indicating the infrared camera model used, the biomechanics marker set and the pendulum ball that the player should hit. The biomechanical markers used (b): 1) *Acromion*; 2) back of the *humeral head*; 3) front of the *humeral head*; 4-6) cluster of the arm; 7) lateral *epicondyle*; 8) medial *epicondyle*; 9-11) cluster of the forearm; 12) *radius styloid process;* 13) *ulna styloid process*. S1 is the IMU sensor located in the arm and S2 is the IMU sensor located in the forearm

Data collection

The elbow joint angle during tennis forehand was measured under laboratory conditions using the NOTCH® IMU system and OS (Qualisys®, Gothenburg, Sweden) with submillimetre accuracy (78). Flexion and extension angles (Fle/Ext [°]), corresponding to the sagittal plane of the elbow and pronation and supination angles (Pron/Sup [°]), corresponding to the transverse plane of the elbow were measured. The following lines explain in detail the characteristics of the IMUs and OS devices and the data collection:

- NOTCH® IMUs system (Wearnotch, Notch Interfaces, Inc., New Jersey, USA): It is a wireless IMU-based system embedded with nine-axis inertial sensors (three-axis gyroscope, three-axis accelerometer, three-axis magnetometer), with a maximum range of measurement of ± 32 g, ± 4000°/s and a maximum sampling rate of 500 Hz (Table 6). The system has been previously validated through functional daily task movements (163). The elbow joint angles from the NOTCH® system were downloaded, thanks to an extended license (which costs $50 USD per year). Static and dynamic sensor calibrations were conducted with the purpose to ensure their optimal performance. A 'steady pose' (anatomical position) was collected prior to each forehand measured, the steady pose was used to capture the orientation of the arm, and thus the NOTCH® IMUs algorithms joined it to a predefined skeleton pose. The IMU was mounted in a rigid plastic case attached to manufacturer-made straps, which were positioned in the segments of the participant. Elbow joint angles measured during all forehands performed during the study were transferred from the NOTCH® Pioneer application to an Android device (Nokia 6.1., Espoo, Finland) via Bluetooth, and then to a server computer for their analysis. Additionally, NOTCH® uses proprietary sensor fusion, filtering methods, and algorithms to calculate joint angles that are restricted for the user.
- Qualisys® optoelectronic system (Qualisys®, Gothenburg, Sweden) consists of nine infrared high-speed cameras (Oqus 300, Qualisys, Sweden), alongside which the Qualisys Track Manager (version 2.17, Qualisys, Gothenburg, Sweden) software was used. All forehands performed during the study were recorded at a sampling frequency

of 500 Hz, and the data were down-sampled to 100 Hz, 250 Hz and 500 Hz to compare the signals with that of the IMUs. An upright static trial was used to create the upper limbs segment (i.e., arm and forearm) and the joint centres (i.e., elbow) posteriorly used in the motion trials. To avoid the brightness disturbances that could be confused with the retroreflective markers, care was taken with the lighting conditions. A calibration wand manufactured by Qualisys® was used for spatial calibration, following the manufacturer's guidelines. The calibration was repeated until obtaining the best possible calibration parameters (the average residuals of the cameras being below 0.4 mm).

Signal processing and filtering

The 3D marker trajectories during the standing position and forehand drive trials were identified by the OS system and exported to C3D format in the Qualisys Track Manager. Then, using the Visual 3D software (V6, C-motion, Inc. Germantown, USA), and based on the University of Western Australia's upper body marker set, the positions and orientations of the dominant arm and forearm were reconstructed and used to compute the elbow joint angles (flexion/extension and pronation/supination). Two different Cardan sequences (AP-AXIAL-ML and ML-AP-AXIAL) were used to calculate pronation-supination and flexion-extension (the motive underlying this relevant decision is explained in the document provided as supplementary material, annexe 3). The elbow joint angle was then filtered forward and backward through an 18 Hz second-order Butterworth filter to obtain the result of a zero-lag fourth-order filter. To select the cut-off frequency of the said filter, an analysis of the residuals was previously carried out (170) using an Excel ad-hoc tool. Based on previous literature (171), every frequency between 1 Hz and 32 Hz at 1 Hz intervals was tested. Residuals (RMSE) were plotted against a cut-off frequency, and a straight line of the best fit was projected back to the y-axis from the linear portion of the residual-frequency curve. A horizontal line was then extended from the vertical-intercept back to the residual-frequency curve, and the frequency at which the two lines meet was chosen as the optimal cut-off frequency (172). This was done for each subject, and the rounded mean (without decimal places) of the cut-off frequency was considered (18 Hz). Finally, elbow joint angles (Fle/Ext and Pron/Sup) from the IMUs and OS were synchronised using an Excel spreadsheet, using a cross-correlation based phase shift technique (159). This procedure of synchronising signals has been used previously in studies to analyse the validity of biomechanical analysis instruments (159,173). This type of synchronisation was chosen given the impossibility of conducting it via electrical pulse (start/stop). The angles from the IMUs were processed unfiltered, as the interest of the study is to analyse the data directly provided by the devices, without any additional data processing. Despite the above, the NOTCH® signal had to be slightly transformed, based on the aforementioned cross-correlation technique, in order to compare it with the OS signal. This transformation is better explained in a document that is added as supplementary material (annexe 6).

Statistical analysis

Descriptive statistics are represented as mean and standard deviation (SD). Tests of normal distribution and homogeneity, determined by the Shapiro–Wilk and Levene's tests, respectively, were conducted on all data prior to analysis. In order to determine the validity of the system regarding the reference system (IMUs vs. OS), the linear relationship and level of agreement between both signals (IMUs vs. OS) were evaluated using Lin's concordance correlation coefficient (Lin's CCC) (174), with a high Lin's CCC indicating the absence of systematic error difference between measurements (175). The following criteria were adopted to interpret the magnitude of correlations between measurement variables: < 0.1 (trivial), 0.1–0.3 (small), 0.3–0.5 (moderate), 0.5–0.7 (large), 0.7–0.9 (very large) and 0.9–1.0 (almost perfect) (131). The magnitude of the error was also quantified by calculating the root mean square error (RMSE) between the two motion capture systems. The RMSE interpretation was based on a previous study (176) as follows: good (RMSE ≤ 2°), acceptable (2° < RMSE ≤ 5°), tolerable (5° < RMSE ≤ 10) and unbearable accuracy (RMSE > 10). For comparing the error of measurement (RMSE) at different sampling rates (100 Hz vs. 250 Hz vs. 500 Hz), one-way repeated measures ANOVA followed by Bonferroni multiple post-hoc comparison tests were carried out. To evaluate the reliability of the sensors of the elbow, a student's t-test for dependent samples was conducted, considering the RMSE and Lin's CCC in the two measurements (test-retest), at each sampling frequency (within-subject error variation). The magnitude of the differences was interpreted using the Cohen's d effect size (ES) (between-group differences) (177) and reported as follows: trivial (< 0.2), small (0.2–0.49), medium (0.5–0.79), and large (≥ 0.8) (177). All data analyses were performed using Excel 2016 and Real Statistic Using Excel Packages (100, 101), and the level of significance used was $p < 0.05$.

4.2.5. Results

Figure 15 shows two examples of the elbow joint angle obtained using the IMUs superimposed on the one obtained with the OS – one for the flexion/extension and another for the pronation/supination.

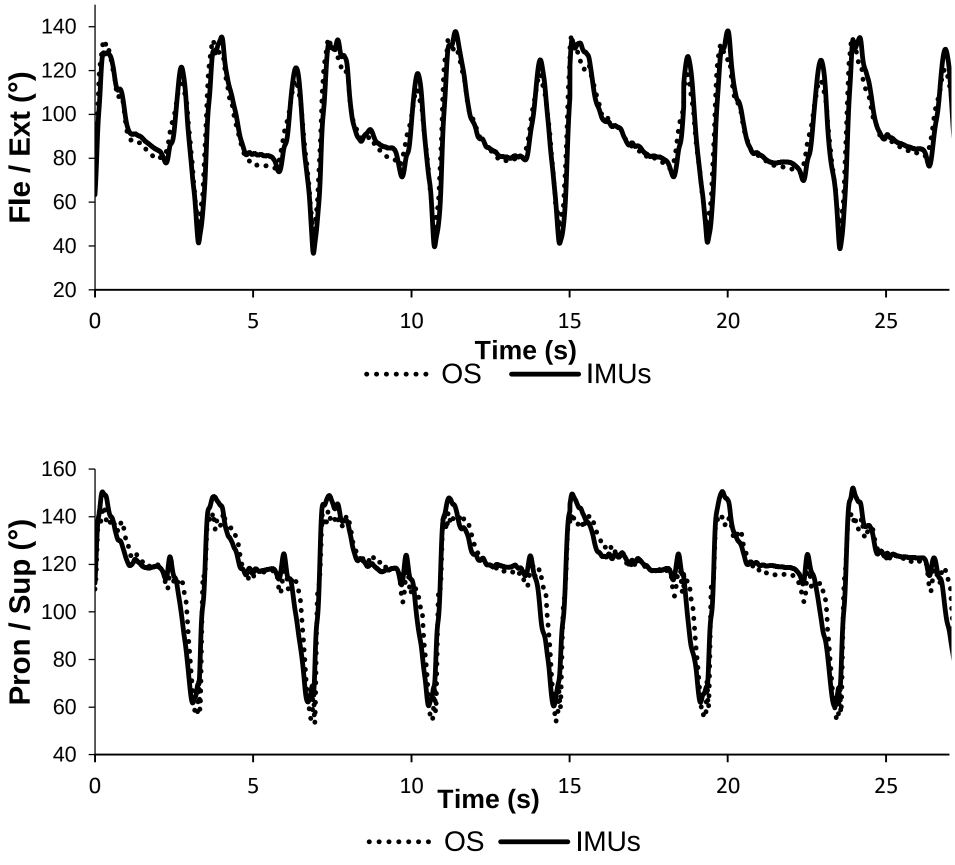


Figure 15. Elbow joint angles during tennis forehand obtained from the OS and IMUs synchronised at 500Hz of one of the study participants

Validity

Table 7 shows a comparative analysis (RMSE and Lin's CCC) between IMUs and OS elbow joint angles at different sampling frequencies (100 Hz, 250 Hz and 500 Hz) during tennis forehand. All the comparisons showed a tolerable RMSE (RMSE < 10). Relative to the correlation analysis (Lin's CCC), very large correlations (r > 0.81) were obtained in all associations between both systems.

Table 7. RMSE and Lin's CCC between elbow joint angles (Fle/Ext and Pron/Sup) obtained from IMUs and OS during tennis forehand at different sampling frequencies (100Hz, 250Hz and 500Hz)

Sample Frequency	Elbow joint angle	RMSE*	Lin´s CCC*
100 Hz	Fle/Ext	8.66°	0.81
	Pron/Sup	8.53°	0.83
250 Hz	Fle/Ext	7.53°	0.85
	Pron/Sup	7.66°	0.86
500 Hz	Fle/Ext	5.76°	0.89
	Pron/Sup	6.66°	0.86

* RMSE: Root Mean Square Error; Lin´s CCC: Lin´s Concordance Correlation Coefficient.

Differences in the error of measurement as a function of sampling frequency

Repeated measures ANOVA showed differences between the RMSE at different sampling frequencies ($p = 0.0024$), and the Bonferroni post-hoc analysis showed no significant differences when comparing 100 Hz vs. 250 Hz, 250 Hz vs. 500 Hz or in flexion/extension nor pronation/supination ($p > 0.05$) (Table 8). Instead, significant differences were found between 100 Hz and 500 Hz in flexion/extension ($p = 0.001$) and pronation/supination ($p = 0.023$), with a large effect size (≥ 0.8) in both cases (Table 8).

Table 8. Bonferroni post-hoc test (from repeated measures ANOVA) between elbow joints angles obtained at the different sampling frequencies

Condition	Mean RMSE (°) (SD)	p-value*	ES*
Fle/Ext 100Hz vs. Fle/Ext 250Hz	8.78 (1.67) vs. 7.27 (1.94)	0.266	0.62
Fle/Ext 100Hz vs. Fle/Ext 500Hz	8.78 (1.67) vs. 5.77 (1.79)	**0.001***	**1.54**
Fle/Ext 250Hz vs. Fle/Ext 500Hz	7.27 (1.94) vs. 5.77 (1.79)	0.068	0.91
Pron/Sup 100Hz vs. Pron/Sup 250Hz	8.41 (1.89) vs. 7.67 (1.15)	0.508	0.48
Pron/Sup 100Hz vs. Pron/Sup 500Hz	8.41 (1.89) vs. 6.67 (1.61)	**0.023***	**1.23**
Pron/Sup 250Hz vs. Pron/Sup 500Hz	7.67 (1.15) vs. 6.67 (1.61)	0.204	0.75

* p-value: significant differences for values lower than 0.05; *ES: Effect size (D-Cohen).

Reliability

The comparative analyses of the RMSE between the test-retest at different sampling frequencies, and in the two anatomical movements analysed showed no significant differences ($p > 0.05$) in any case (Table 9). This indicates that the error was consistent between measurements. Regarding the Lin's CCC between devices, it always remained above 0.8, and no significant differences ($p > 0.05$) were found between the test-retest or in any comparisons.

Table 9. Comparison of the RMSE and Lin's CCC between test-retest at different sampling rate and in different anatomical movements (Fle/Ext and Pron/Sup)

Sample rate	Elbow joint angle	RMSE (°) mean (SD)		p-value	Lin's CCC mean (SD)		p-value
		Test	Re-test		Test	Re-test	
100 Hz	Fle/Ext	8.78 (1.67)	9.14 (2.50)	0.48	0.81 (0.14)	0.81 (0.13)	0.75
	Pron/Sup	8.41 (1.89)	8.67 (1.92)	0.65	0.83 (0.06)	0.82 (0.08)	0.55
250 Hz	Fle/Ext	7.27 (1.94)	6.71 (1.49)	0.12	0.85 (0.1)	0.88 (0.07)	0.23
	Pron/Sup	7.67 (1.15)	7.58 (1.83)	0.86	0.86 (0.08)	0.87 (0.07)	0.69
500Hz	Fle/Ext	5.77 (1.79)	6.06 (2.24)	0.71	0.89 (0.06)	0.86 (0.09)	0.24
	Pron/Sup	6.67 (1.61)	6.57 (1.37)	0.89	0.86 (0.07)	0.89 (0.06)	0.17

* p-value: significant differences for values lower than 0.05

4.2.6. Discussion

The aim of the present study was to analyse the concurrent validity and reliability of a IMUs system for measuring the elbow joint angle during forehand strokes, comparing the data against an OS (gold standard). The RMSE of the transformed signal was tolerable (5° < RMSE ≤ 10) for all anatomical movements and sampling frequencies. The Lin's CCC between both devices was very large (0.7–0.9) in all cases. The RMSE increased significantly ($p > 0.05$) in the recordings made at 100 Hz as compared to those made at 500 Hz, for both planes of the elbow (flexion/extension and pronation/supination), with a large effect size (≥ 0.8) in both planes. The within-subject error variation between test-retest showed no significant differences in any of the elbow planes and sampling frequencies used, and the level of agreement also remained > 0.8 in all cases.

Previous studies (79, 185) have suggested that a RMSE below 10° demonstrates very good accuracy of the IMU devices. The error of measurement of the IMUs were below this threshold for the two planes of the elbow and all the sampling frequencies used. If we compare the results with those of studies that have analysed IMU validity, we will find similar values for the agreement and RMSE scores, relative to the upper limb kinematics. For example, Fantozzi et al. (160) found RMSE of 15° and 10° in the sagittal and transverse planes of the elbow while swimming, whereas Barreto et al. (178) found similar correlation coefficients and RMSE in the elbow during gymnastics skills. Tennis strokes have a particular idiosyncrasy as they are usually executed at a high-speeds, thereby achieving high angular velocities, especially in the last segments of the kinetic chain (that is, at the elbow and at the wrist). For this reason, validation studies of the specific IMUs for this sport should be carried out, especially considering that the speed could affect the accuracy of the measurement (67). A similar study (83) analysing IMU accuracy while performing tennis forehands reported a Lin's CCC > 0.9 and a RMSE below 2° in the sagittal plane of the elbow (flexion/extension), only slightly better than the present investigation. In contrast, for the elbow pronation-supination angle, data from the present work (Table 6) showed a higher level of agreement and a lower RMSE than in the study of Pedro et al. (83) (they reported Lin's CCC of 0.79 and RMSE of 13.1°). The differences in precision of the different IMUs evaluated could be predominantly attributed to the biomechanical models and different calibration methods (161). The threshold beyond which the error will be considered large also depends on the objectives of the investigation. For example (179), found differences of about 16° for the elbow flexion angle at impact between prepubescent's and adults. This value is higher than the RMSE of the NOTCH® sensors, thus concluding that this device is sufficiently accurate to detect the differences in this particular case. On the other hand, (153) found differences between elite- and high-performance players below one degree for the elbow flexion angle during the forehand strokes, probably requiring, in this case, a more accurate system.

In the present study, it was found that the error (measured as RMSE) increased significantly ($p < 0.05$), if we compare the recordings made at 100 Hz and 500 Hz. This result supports the hypothesis of previous studies (62, 209) which indicate that a minimum sampling frequency of 200 Hz is required for an accurate upper limb's kinematic analysis of tennis strokes. Despite the differences found, the level of agreement and the magnitude of the error of the recordings made at 100 Hz were very large (0.8–0.9) and tolerable (RMSE < 10°) in all cases, with values similar to that of the literature (184, 185). Therefore, recording at 100 Hz with the present sensors could be appropriate when the researcher is interested in collect long recordings and wants to measure, for example, the physical load in a competition (210, 211). In this case, the sampling rate required does not have to be as high as when the main interest of the research is, for example, comparing the hitting kinematics between players of different levels of performance (39, 177). Finally, the magnitude of the error remained constant ($p > 0.05$) throughout the course of the test-retest, and the level of agreement was > 0.8 in all planes of the elbow and sampling frequencies used, which indicates the reliability of the IMUs.

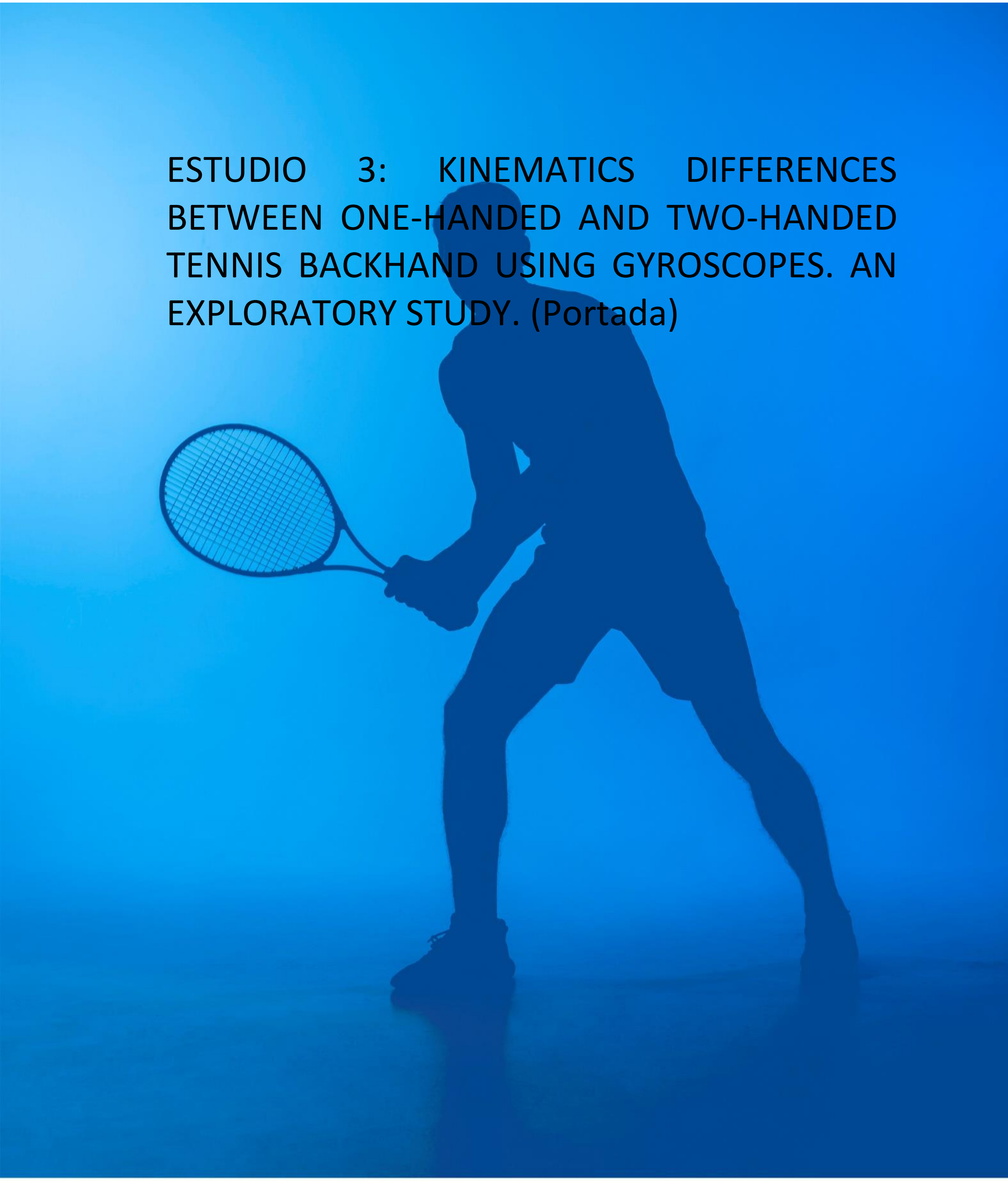
Summarising, NOTCH® IMUs could be an alternative (transforming the signal by using a simple linear equation) to other sensors that have been more tested in the scientific field and are supported by a large number of high-impact publications (83). The sensors used in the present manuscript have three notable advantages over other models used for biomechanical analysis: I) low price, which allows laboratories with a limited budget to use them; II) the measurement range of gyroscopes (± 4000 degrees per second) that allows evaluating ballistic gestures such as tennis strokes, where sometimes 2000 degrees/s are exceeded (84); III) their capability to measure at high sampling rates (500 Hz) which allow them to analyse tennis strokes in detail, and even capture the moment of the ball impact with the tennis racket. Another real use of these sensors would be the design and implementation of systems for the detection, classification and evaluation of strokes in real competition situations (183–186). Finally, the NOTCH® sensor can be considered an economical and valuable tool for field-based experimentation.

Study limitations are associated with iron structures within laboratories that may interfere with electronic devices for data collection and the sample size used since it was not determined by statistical methods. Despite this, level of agreement between both measurement systems was strong, and the differences (measured as RMSE) seem small enough to detect differences in elbow angulations during tennis forehand. IMUs allow evaluating in natural playing conditions, something which, until recently, was difficult to do with traditional photogrammetric systems. Others limitations of the study is that the IMU and OS system signals could not be synchronised by electrical pulse and that the S2 and forearm marker cluster were not attached together. Therefore, we believe that work that analyses the validity of these devices in a controlled laboratory situation is very necessary and should be done before using them to evaluate the kinematics of hitting the field. Further research is required to check the validity and reliability of the NOCTH® measurements in different anatomical joints and strokes. Also, future studies could include other IMUs (e.g., Xsens) attached to the same location as NOTCH® (on top of each other), and the same analysis could be performed on both. This is because, obtaining RMSEs of < 10° in a limited testing condition (limited number of trials, limited duration of the test, limited number of participants, limited type of motions) does not truly reveal the validity of the IMUs. However, given the errors of another well-established IMU, such as Xsens, a reader could understand the true potential of the NOTCH® sensors. Also, it would be important to conduct an independent study to validate the orientation measured with proprietary sensor fusion of NOTCH®. The characteristics of these sensors (high sampling frequency and high measurement ranges of the accelerometer, gyroscope and magnetometer) and the possibility of programming them via an API provided by the manufacturers (wearnotch.com) make them ideal for advanced biomechanics assessment in tennis.

4.2.7. Conclusions

This is the first study to analyse the validity of IMUs for measuring elbow joint angles by comparing data with an optoelectronic system, at different sampling frequencies during tennis forehand. The results indicate that the NOTCH® inertial measurements system is a valid and reliable tool to measure elbow joint angles during tennis forehand. Even though all sampling frequencies analysed (100 Hz, 200 Hz and 500 Hz) showed good validity and reliability scores, the best results were obtained at 500 fps, so it is recommended to use this sampling frequency for short recordings (wherein the memory or the computation time is not a concern). Finally, although a simple signal transformation must be applied before use, NOTCH® sensors can help develop and refine technical actions and to correct biomechanical inefficiencies. Also, the potential of a low-cost tool will be an aid for tennis coaches and sports science researchers, who have limited access to laboratory evaluations.

ESTUDIO 3: KINEMATICS DIFFERENCES BETWEEN ONE-HANDED AND TWO-HANDED TENNIS BACKHAND USING GYROSCOPES. AN EXPLORATORY STUDY. (Portada)



4.3. ESTUDIO 3: KINEMATICS DIFFERENCES BETWEEN ONE-HANDED AND TWO-HANDED TENNIS BACKHAND USING GYROSCOPES. AN EXPLORATORY STUDY

Este estudio ha sido publicado en la revista *International Journal of Racket Sports Science,* en el año 2022, volumen 4, número 1, páginas 16-24. Sus autores fueron: Emilio J. Ruiz-Malagón; Gabriel Delgado-García; Maximiliano Ritacco-Real; Víctor M. Soto-Hermoso.

4.3.1. Resumen

El objetivo principal de este estudio fue comparar la cinemática angular y la coordinación intersegmentaria de miembros superiores entre el revés a dos manos y a una mano en una muestra de 20 jugadores masculinos de competición mediante el uso de giróscopos. Además de, comparar la velocidad y precisión de la pelota obtenida en ambos tipos de revés. La cinemática angular, la coordinación intersegmentaria, la velocidad de la pelota y la precisión se compararon durante un test de golpeo específico utilizando cuatro sensores inerciales (tronco, cabeza, brazo y antebrazo). Se encontraron diferencias significativas en términos de ω_{pico} y coordinación intersegmental en algunos de los segmentos medidos entre DH y SH mediante el uso de giroscopios, pero ocurrió lo contrario en las variables velocidad de la pelota y precisión ya que no se encontraron diferencias significativas entre el revés a una mano y el revés a dos manos en términos de velocidad y precisión. Sin embargo, se encontraron velocidades angulares máximas más altas en el tronco y el brazo sobre el eje x en el revés a dos manos, lo que podría indicar que este tipo de revés genera una mayor rotación del tronco y rotación externa del brazo y antebrazo en comparación con el revés a una

mano. Las velocidades angulares máximas fueron mayores en el brazo y antebrazo en el eje z en el caso del revés con una mano, lo que se relaciona con una mayor extensión del antebrazo acompañada de una mayor terminación del gesto técnico. En conclusión, el modelo propuesto de análisis biomecánico mediante el uso de giroscopios es especialmente útil para el análisis cinemático de los golpes de tenis en situaciones reales de juego y podría adaptarse fácilmente a otros deportes de raqueta. También es una alternativa portátil y de bajo costo que incluye toda la instrumentación y procesamiento de datos.

Palabras clave: wearable; sensor inercial; velocidad angular; miembros superiores; deportes de raqueta.

4.3.2. Abstract

The main objective of this article is to compare angular kinematics and intersegmental coordination of the upper limbs between two-handed and one-hand backhands in a sample of 20 male competition players by using gyroscopes and compare ball speeds and accuracy obtained in both types of backhand. The angular kinematics, intersegmental coordination, ball speed and accuracy were compared during a specific stroke performance test using four inertial sensors (trunk, head, arm and forearm). We hypothesize that significant differences will find in terms of ω_{peak} and intersegmental coordination in some of the segments measured between DH and SH by using gyroscopes, but the opposite will happen in the variables speed ball and accuracy. There are no significant differences between one-handed backhand and two-handed backhand in terms of speed and accuracy. Although, higher peak angular speeds were found in the trunk and arm over the x axis in two-handed backhand, which could indicate that this type of backhand generates

greater trunk rotation and external rotation of the arm and forearm compared to one-handed backhand. The peak angular speeds were greater in the arm and forearm on the z axis in the case of one-handed backhand which is related to a greater extension of the forearm accompanied by a higher termination in the technical gesture. In conclusion, the proposed model of biomechanical analysis through the use of gyroscopes is especially useful for kinematics analysis of tennis strokes during field-based experimentation and could easily be adapted to other sports. It is also a low-cost and portable alternative that includes all instrumentation and data processing.

Keywords: Wearable; inertial sensors; angular speed; upper body; racquet sports.

4.3.3. Introduction

Physical fitness, motivation and tactical dexterity are important aspects to get a good performance in tennis, but the mechanical efficiency of the player´s strokes often determines the level of success both recreationally and competitively (187). Although the forehand allows generating more speed, effect of the ball and accuracy after the impact than backhand, this is also a basic groundstroke and is becoming increasingly important in modern tennis (188–190). A player decision to use two-handed backhand (DH) or one-handed backhand (SH) is a key point in the tennis learning process, since he will be able to obtain a major or minor biomechanical efficiency in this stroke depending on his decision (26). For example, DH is the type of backhand that most of the baseline players usually choose, while the versatile players seem more likely to choose SH because it is easier for them making net approach strokes and backhands volleys (26). Young tennis players prefer DH during their initiation phase since it requires less force than SH (45). Another factor that favors the selection of DH over SH in adult beginner players is that SH is more susceptible to tennis elbow (45, 46, 220).

There is a need to carry out research that analyses the kinematics of the backhand since it is less studied than forehand or serve (26, 221), since backhand is one of the two basic groundstrokes in tennis and the evolution of the backhand represents one of the biggest changes in tennis over the past decades (26). The segments used for performing both backhands (DH and SH) are the same: hips, shoulder, upper arm and hand/racket rotation (193). Instead, 3D photogrammetry research indicates biomechanical differences between DH and SH (26, 45, 223). These studies show a sequential coordination between the different segments involved in performing the two backhands (195). It has been shown that CI occurs from proximal to distal in terms of angular velocity and linear velocity (25) and that the moment of maximum trunk rotation acquires a fundamental character in the performance that we can achieve in this stroke (26).

The biomechanical parameters of tennis strokes have been widely studied in laboratory conditions, but there is a shortage of studies that do it on the court (195). Only some biomechanical studies make of use inertial sensors in tennis (212, 225), however after reviewing the literature, in most cases the devices are placed on the racket or forearm, and tennis performance is the result of sequenced whole body coordination (195). It will be vital also to analyse the trunk, arms and head to have a more complete monitoring of the kinematics of the stroke (197).

Previous studies have shown that inertial measurement unit (IMU) gyroscopes are a valid alternative to 3D optical motion capture system for angular kinematics analysis in tennis (67) since they allow capturing the rotational movements in the three axes of space; record the peak angular speeds (ω_{peak}) of the different segments and differentiating between different levels of play (198). They also allow to discriminate the different phases of the strokes (228, 229) and obtain the sequencing of the segments that are part of the kinematics of the stroke (200).

The main objective of this article is to compare angular kinematics and intersegmental coordination of the upper limbs between two-handed and one-hand backhands in a sample of competition players by using gyroscopes. In addition to comparing ball speeds and accuracy obtained in both types of backhand. We hypothesise that significant differences will find in terms of ω_{peak} and CI in some of the segments measured between DH and SH by using gyroscopes, but the opposite will happen in the variables speed ball and accuracy.

4.3.4. Methods

Sample

A sample of 20 male advanced players with a minimum of 15 years of experience (all of them were taking part in regional competitions) was used, 10 with DH and 10 with SH. The age range of the sample was 17 to 49 (29.55 ± 8.16) years. The anthropometric characteristics of the participants were obtained using the Inbody 230 bioimpedancemeter (Inbody Seoul, Korea). The average height of the sample was 177.33 cm ± 5.5 (means ± standard deviation), weight 79.3 Kg ± 12.66, body mass index 25.9 ± 3.94, body fat mass 15.76 Kg ± 9.34 and skeletal muscle mass 35.22 Kg ± 4.48. Participants were instructed to have fasted in the previous two hours and not to have performed strenuous physical exercise in the 48 hours prior to the study.

Sample exclusion criteria were musculoskeletal injury and the use of medications that could cause problems during the test. After receiving detailed information on the objectives and procedures of the study, each subject signed an informed consent form in order to participate, which complied with the ethical standards of the World Medical Association's Declaration of Helsinki (2013). It was made clear that the participants were free to leave the study if they saw fit. The study was approved by the Institutional Review Board.

Procedures

Specific stroke performance test

The test was performed on indoor court with type A surface (106). Each player used their own racket, which was previously checked to ensure that it was in good condition according to the criteria of the International Tennis Federation (106). Since the tension of the racket strings affects the control and the power of the stroke (201) it was measured with a tensiometer (Tourna stringmeter, EE.UU). The tensions of the rackets were in a range of 19 to 25 kilograms. Sixty new and well-pressurized tennis balls (Wilson Trainer) with weight and size characteristics were used within the standards allowed by the ITF (106). The tennis ball machine (Lobster Gram Slam 4, Lobster Sport Inc. North Hollywood, CA. EE.UU) it was calibrated before the start of each test following the manufacturer's instructions. Before starting the test, participants performed a standardized 8-minute warm-up divided into general warm-up (mobility exercises) and specific that it consisted of a 5-minute rally with a high-level player (it was the same for all participants). The subjects were given a heart rate monitor with the aim of controlling heart rate and thus preventing fatigue from being a contaminating factor during the development of the protocol. The next stroke series was not started until the subject reached a difference maximum of 10 ppm regarding the pulsations measured just after warm-up (107).

After the warm-up, the protocol was explained to the subjects. The stroke protocol is based on previous study of Lyons et al., (107). A total of 600 backhands were recorded (300 DH and 300 SH). To ensure that the time between strokes was constant in all subjects and in all series the resultant angular speed (R_ω) of the forearm sensor was used, taking the moment of appearance of the peaks (each peak was considered an impact), following a similar process from a previous study to detect falls (202). The total average time between strokes was 3.42 ± 0.025 seconds. The test consisted of three stroke series (alternating forehand and backhand) with 20 strokes each. The participants always had to hit parallel trying to send the ball to the different objectives of the opposite court (figure 16). The players were asked to "achieve the objectives with the greatest possible speed", similar indication to that made in previous studies of stroke accuracy (39, 232). The Stalker Pro II speed radar (Stalker Radar, Plano, Texas) was placed in the center of the track and was oriented parallel to the lateral lines with the intention of minimizing the error due to the angle of the trajectory of the ball (204). The ball bounce was recorded at 60 fps with a rear and aerial viewpoint using the Panasonic HC-V160EC-K camera (Panasonic, Japan) with the aim of obtaining the accuracy achieved by each player. The accuracy of each shot was evaluated according to the area of the court where the ball had bounced (Figure 16). The balls that bounced off these targets were scored with zero. The total accuracy was calculated as the percentage of points obtained in relation to the total points possible.

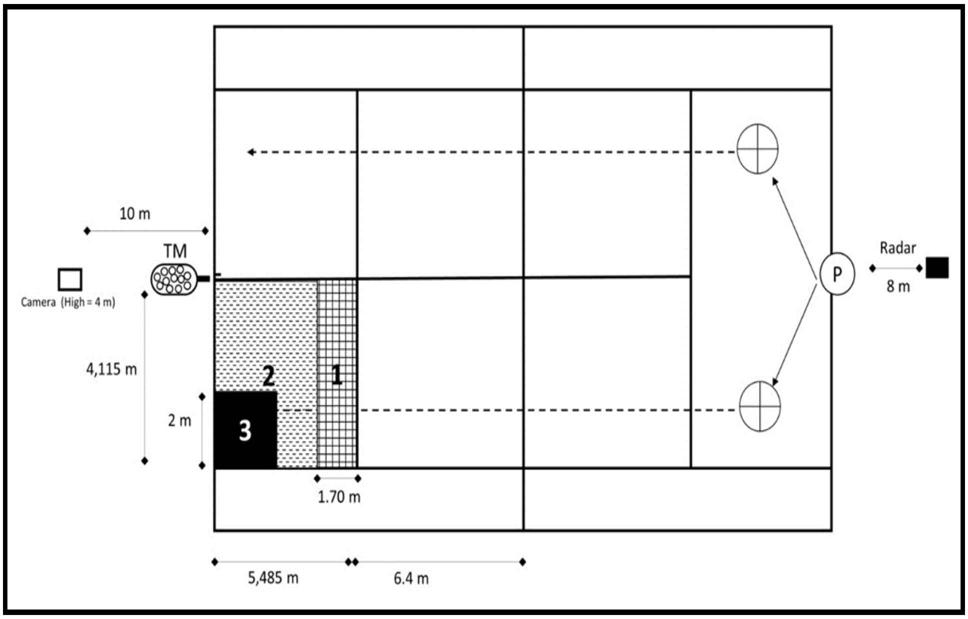


Figure 16. Stroke test with the dimensions and scores of the targets. The targets for the bottom shots are represented by the values 1, 2 and 3. The numbering of each zone corresponds to the score awarded to the participant. TM: Tennis ball machine

Analysis of the gyroscope signal

A peak analysis of the gyroscope signal (Nexgen Ergonomic, Montreal, Canada) was performed in order to find both the magnitude and the moments of maximum rotation (rad s^{-1}) of different segments during each stroke. 5 sensors (Nexgen Ergonomic, Montreal, Canada) were placed on the trunk, head, arm, and dominant forearm. This sensor location follows the guidelines of previous works (67, 227, 234). Locations and own axis of each sensor is shown in Figure 17. They were used at a sampling frequency of 128 Hz and record synchronously between each other. According to the manufacturers x and y axis gyroscopes has a range of ± 2000 deg s^{-1} and a typical noise density of 0.81 mrad/s/$\sqrt{hz}$ and the z axis has a range of 1500 deg s^{-1} and a typical noise density of 2.2 mrad/s/$\sqrt{hz}$.

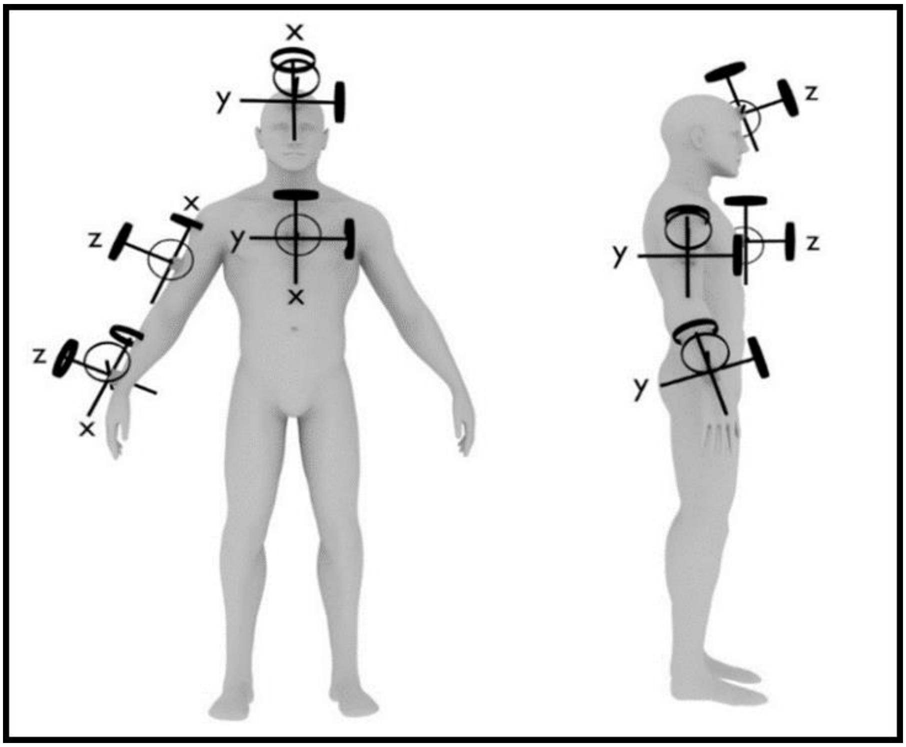


Figure 17. Positioning of the sensors and rotation axes. The circles represent the plane of rotation. The rotations on the x axis correspond to the turns on the longitudinal axis of the segment

To verify the validity of the inertial sensors, an internal validation study was carried out with five subjects of different levels. The gyroscope signal was compared with a 3D photogrammetric analysis system (OptiTrack, Natural Point Corvallis, USA) and analyzed with Visual 3D (c-Motion, Inc., Rockville, MD, USA). The gyroscopes were placed in the same locations that in the stroke test described previously and each subject executed 5 series (2 series of forehands, 2 series of backhands and 1 series of serves) of 20 strokes each series hitting a ball fixed in an elastic bar (laboratory conditions). The signals of angular velocity in each of its axis (x, y and z) acquired with both systems (sensors gyroscopes and markers-based gyroscopes) was compared. For this, 300 correlations were made in which the average r was 0.985 ± 0.018 in forehand and backhand situations with and without the ball.

Angular Kinematic

The original unfiltered gyroscope signal was used to not modify the height of ω_{peak}. A semi-automatic peak search was carried out using the Origin 9 software (OriginLab Northampton, MA), with the function of the software "peak analysis". It was visually verified that the peaks were correctly selected with the TK Motion Studio software (APDM Inc, Portland, OR, USA), which allows us to capture the synchronized signal with a GoPro video camera (GoPro Inc., San Mateo, CA) set at 60 fps, so that strange peaks can be identified and discarded. This analysis aimed to find both the magnitude and the moments of maximum rotation (rad/s) of the different segments during each stroke of the series. Taking into account the duration of a stroke and in order to avoid false positives, only those ω_{peak} that were found at ± 25 samples of the moment of appearance of the resulting peak of angular speed of the forearm ($R\omega_{peak}$ of the forearm). Other authors have also used the $R\omega_{peak}$ to determine events (202).

Intersegmental coordination

A comparison of the IC was made between ω_{peak} of the forearm (reference sensor) and ω_{peak} of the trunk, ω_{peak} of the head and ω_{peak} of the arm, for DH and SH. IC is related to the sequence of movements of the aforementioned segments. Other authors (71) have used the moment when the segment begins to rotate (angular velocity changes sign and increases or decreases significantly). However, in the present work it has been preferred to select the $\omega_{peak,}$ since in such explosive gestures as tennis strokes the moment of rotation start is more difficult to detect because the signal changes sign at several points on the x axis. In the case of trunk and arm, ω_{peak} were selected on the x axis (which corresponds to the longitudinal axis of these segments), where it is expected greatest angular speed will be found (due to the moment of inertia with a lower rotation radius). In the case of the head, the resulting was selected ($R\omega_{peak}$ of the head), since it is more complex to determine the axis of rotation on which the maximum angular velocity occurs (the neck joint allows more degrees of freedom). The unit of IC is the number of samples. This unit can be transformed into time by dividing it by the sampling frequency of the sensors (128 Hz). Finally, IC was calculated by subtracting the moment of appearance of the ω_{peak} of the segment in question (trunk, head and arm) at $R\omega_{peak}$ of the forearm. $R\omega_{peak}$ of the forearm was considered the closest point to the impact of the ball. Bourke & Lyons (202) also used Rω but in a sensor placed on the trunk. In our study, a positive value in Rω indicates that the peak appears after the moment of impact and vice versa.

Statistical analysis

Descriptive statistics are represented as mean and standard deviation. Tests of normal distribution and homogeneity, determined by the Kolmogorov Smirnov and Levene's test, respectively, were conducted on all data before analysis. The accuracy of each participant was presented as the percentage of points achieved with respect to the total (90 points) and the speed as the average speed of all their hits. Unpaired comparisons of means (t-test) were conducted between data from the two types of backhands for the variables stroke speed (km/h) and accuracy (%). The magnitude of the differences between values was also interpreted using the Cohen's d effect size (*ES*) (between-group differences (177). Effect sizes are reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) [30]. In contrast, the ω_{peak} and IC of the different segments analysed did not follow a normal distribution. Therefore, a Mann-Whitney-Wilcoxon independent means comparison test was performed. The level of significance used was $p<0.05$. All statistical analyses were performed using the Origin 9 software program (OriginLab Northampton, MA), except the effect sizes that were calculated with the Psychometric freeware (114).

4.3.5. Result

In table 10 we can see a comparison of the average speeds generated to the ball and the accuracy (%) of both types of backhands (SH and DH). Where despite the fact that the DH values are slightly higher for both average ball speed and accuracy, no significant differences were found between them (P> 0.005).

Table 10. Comparison of average ball speed and accuracy between DH and SH of all participants

Players **(SH)**	Ball speed *	Accuracy %	Players **(DH)**	Ball speed *	Accuracy %
1	103.2	61	1	90.8	32
2	104.4	33	2	103.2	58
3	89.6	37	3	96.9	35
4	103.9	46	4	87.9	43
5	96	52	5	76.9	31
6	82.5	52	6	82.5	45
7	94.3	43	7	82.8	36
8	92.3	40	8	87.5	60
9	81.1	34	9	92.3	36
10	98.9	42	10	90.1	43
Total	89.09 ± 7.52*	42 ± 0.1*	**Total**	94.62 ± 8.41*	44 ± 0.08*

* Means ± standard deviation; * Average ball speed

Figure 18 shows the comparison of the mean of ω_{peak} between DH and SH. Significantly higher ω_{peak} (rad / s) were obtained for the DH on the x axis of the sensors placed on the trunk and arm, and on the y axis of the sensor placed on the forearm. The effect size was large in the three cases (> 0.8). In the case of SH, ω_{peak} higher were obtained on the z axis of the sensors placed on the forearm and arm. Being in the case of the arm a moderate effect size (0.5-0.79) and in the forearm a large effect size.

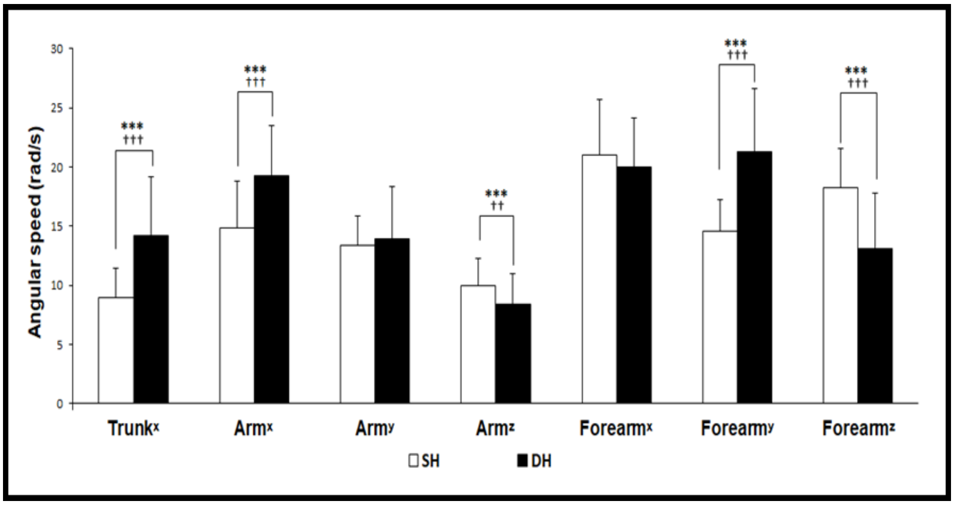


Figure 18. Comparison of the average of ω_{peak} between the two types of backhands on the different segments analysed (SH and DH). * p <0.025; ** p <0.01; *** p <0.001; * † small effect size; †† medium effect and ††† large effect

Figure 19 represents the IC in relation to the temporal differences in the appearance of the ω_{peak} of the analysed segments, taking as reference $R\omega_{peak}$ of the sensor placed in the forearm, between DH and SH. Significant differences were found in the appearance of the ω_{peak} of the sensors placed on the arm and head between DH and SH. The effect size was small in both cases (0.2-0.4). There were no significant differences in the appearance of the ω_{peak} between DH and SH in the sensor placed in the trunk.

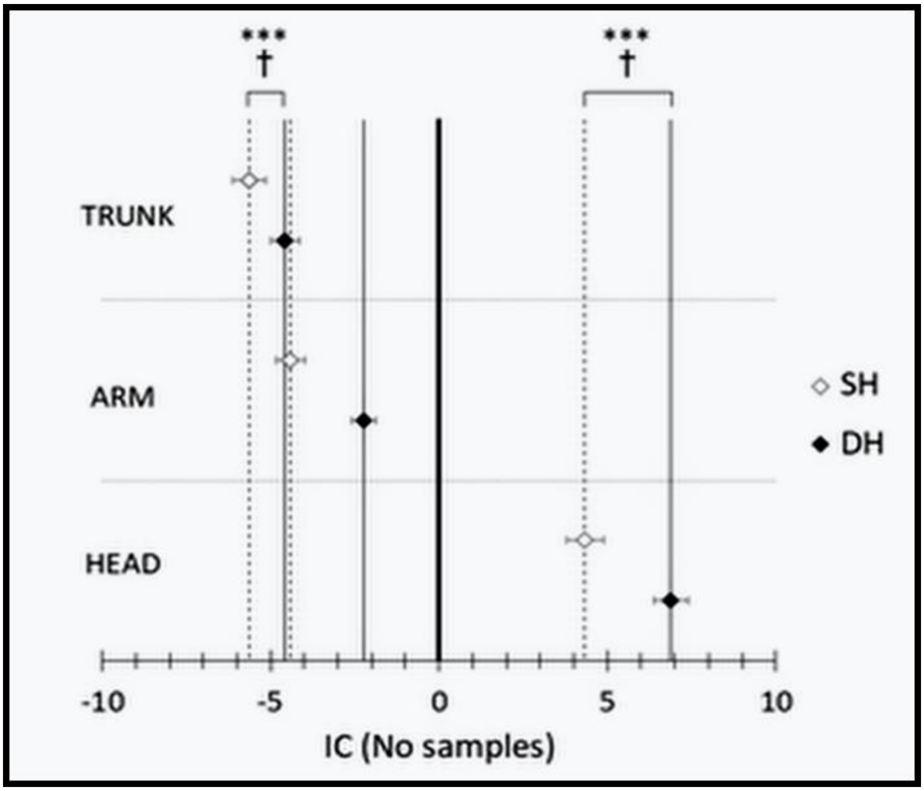


Figure 19. Comparison of the IC in the appearance of ω_{peak} in analysed segments taking as reference $R\omega_{peak}$ of the sensor placed in the forearm, between the DH and SH. Black rhombuses correspond to DH and white rhombuses with SH. * $p < 0.025$; ** $p < 0.01$; *** $p < 0.001$; † small effect size

4.3.6. Discussion

Ball speed and accuracy

The average ball speed in SH was 89.09 ± 7.52 Km/h while that in DH was 94.62 ± 8.41 Km/h, although it is slightly higher in the DH no significant differences were found between them. Previous studies found that there are no differences in the ability to generate ball speed between DH and SH (206). Regarding the accuracy obtained in the stroke performance test, no significant differences were found between DH and SH (42% vs 44%), which corroborates the results of previous studies (44, 236), which also did not find differences in accuracy comparing DH and SH. Both our results and of the literature consulted suggest that racket speed, ball speed and the accuracy of the stroke should not be affected by the type of backhand used; other factors such as kineanthropometry, coordination skill or player style will determine these variables (193). Thus, our hypothesis is fulfilled since there are no significant differences in terms of ball speed and accuracy between DH and SH.

Angular Kinematic

In the present study biomechanical differences have been obtained in the ω_{peak} between DH and SH through the use of gyroscopes, which coincides with the results of the previous studies (26, 45, 47, 49, 222) in which similar differences were detected comparing both types of backhands by using 3D photogrammetry. Significantly larger ω_{peak} were obtained in the sensors placed on the trunk and arm on the x axis (rotational movements on the longitudinal axis) for DH, it is consistent with previous studies (26, 48) since both studies conclude that this type of backhand generates greater trunk rotation and external rotation of the arm and forearm compared to SH. They were also found ω_{peak} significantly larger for the sensor placed in the forearm on the y axis in the DH, but after reviewing the literature we have not found references that justify the finding. Instead, they were found greater ω_{peak} in the SH in the sensors placed on the arm and forearm on the z axis, which conforms to the results of Knudson & Blackwell (44) and Reid & Elliot (193) who detected a greater extension of the forearm accompanied by a higher termination in the technical gesture of the SH compared to the DH in a sample of competitive tennis players. In order to talk about anatomical movements based on ω_{peak} (captured with inertial sensors) in the different axes, we have to rely on the results of Choppin et al. (47) that indicate that the angle between the face of the racket and the vertical is from 14 to 33 degrees. Taking into account the anatomy of the wrist, if the player will use an east grip or a little more closed such angle would make the forearm practically perpendicular to the ground, so that the y axis sensor would be parallel to the vertical and therefore a greater movement in z axis will indicate that the trajectory of the racket follows a path with greater vertical component (36).

Intersegmental coordination

The comparison of the IC of the ωpeak between both types of backhand showed that both meet a sequential coordination between the different segments involved in the realization of the stroke (195). In addition, as in the study by Marshall and Elliott, (25) such sequential coordination occurs from proximal to distal in terms of angular speed and linear velocity for both, SH and DH. The point of maximum trunk rotation in the DH is significantly closer to the moment of maximum rotation of the forearm than in the SH, which could indicate that the hip begins to rotate earlier during two-handed backhand. The biomechanical differences found between DH and SH in terms of ωpeak and intersegmental coordination in some of the segments measured using gyroscopes confirm our initial hypothesis.

Head stabilization

In other sports where precision is an important factor, inertial sensors have been used to study the movements of the head (208) but there are not many scientific studies about the movements of the head during a tennis stroke (34). Yet, gaze direction is a subject of great interest for tennis coaches (209). In our study, there were significant differences in the moment of appearance of the ω_{peak} of the head. It is difficult to discuss these results since the movement of the neck depends to some extent on the movement of the trunk (*this needs to be further studied)*. This ω_{peak} of the head during the impact could affect the movement control and the accuracy of the stroke, as can be deduced from the conclusions of the study by Lafont (209), who revealed that elite players show a characteristic head fixation in the direction of the contact zone at impact and during the follow-through. It is not clear if this head fixation is more related to maintaining a stable head and body position during skill execution or to the need to extract operational information from the ball (209).

Five-marker model has been the most used with 3D photogrammetric systems to analyse biomechanical differences between DH and SH (43, 221, 222). In contrast, in our study with inertial sensors, four sensors have been used since the legs sensors were suppressed in order to capture only the kinematics differences of the upper body (198). The results of the present study should be interpreted with caution because of possible errors when performing analysis of human movements (194). Placed instruments may also contain a source of error due to skin movement (210). Another limitation of the study was the number of participants used and their play level (intermediate). In future studies, the sample will be significantly increased and only competitive tennis players will be measured. In addition, it might be interesting for future studies to determine the maximum speed without to obtain a reference value. It could be that and athlete increases their accuracy at the expense of speed.

4.3.7. Conclusion

The proposed model of biomechanical analysis with gyroscopes is especially useful for the kinematic of tennis strokes during field-based experimentation and could easily be adapted to other hit sports with and without implements. It is also a low-cost and portable alternative that includes all instrumentation and data processing respect to others motion capture systems. Our hypothesis is fulfilled in the light of the results of the study. There are no significant differences between one-handed backhand and two-handed backhand in terms of speed and accuracy. Although it has been shown that there are significant biomechanical differences between two backhands, higher peak angular speeds were found in the trunk and arm over the x axis in two-handed backhand, which could indicate that this type of backhand generates greater trunk rotation and external rotation of the arm and forearm compared to SH. The peak angular speeds were greater in the arm and forearm on the z axis in the case of one-handed backhand which is related to a greater extension of the forearm accompanied by a higher termination in the technical gesture. Both types of backhands followed a sequential coordination from proximal to distal, but in the two-handed backhand the moment of maximum trunk rotation was located significantly closer to the point of maximum rotation of the forearm compared with one-handed backhand.

ESTUDIO 4: FIELD-BASED UPPER-BODY MOTOR VARIABILITY AS DETERMINANT OF STROKE PERFORMANCE IN THE MAIN TENNIS STROKES (portada)

4.4. ESTUDIO 4: FIELD-BASED UPPER-BODY MOTOR VARIABILITY AS DETERMINANT OF STROKE PERFORMANCE IN THE MAIN TENNIS STROKES

Este estudio ha sido publicado en la revista *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology,* en el año 2023. Sus autores fueron: Emilio J. Ruiz-Malagón; Jos Vanrenterghem; Maximiliano Ritacco-Real; Francisco T. González-Fernández; Víctor Manuel Soto-Hermoso; Gabriel Delgado-García.

4.4.1. Resumen

El rendimiento en tenis depende en gran medida de la repetición hábil de varios tipos de golpes de tenis; sin embargo, el papel de la variabilidad motora ha recibido poca atención científica, especialmente a nivel intrasujeto. El presente estudio tiene como objetivo evaluar el papel de la variabilidad motora en función de los golpes, segmento corporal y el nivel de experiencia. Treinta y cinco jugadores realizaron una prueba de golpeo en pista (se analizaron primer y segundo servicio, golpes de derecha y de revés) con cuatro giróscopos sincronizados colocados en el tronco, la cabeza, la parte superior del brazo y el antebrazo. La variabilidad se midió en base al coeficiente de variación (CV) de los picos de velocidad angular en cada segmento del cuerpo durante los golpeos. El test MANOVA reveló una mayor variabilidad motora en el golpe de derecha y el revés que en el servicio ($p < 0.001$), siendo los segmentos de la cabeza y el antebrazo los que mostraron la mayor variabilidad ($CV > 15$ % en algunos casos). Este resultado también se tradujo en diferencias en la variabilidad entre niveles de experiencia, siendo la variabilidad mayor entre los jugadores de niveles inferiores ($p < 0.02$ en

todos los golpes, con Cohen d > 1 en algunos casos). En resumen, los golpes de fondo podrían implicar movimientos cinemáticos más compensatorios para mantener estable el resultado de la acción. Se debe considerar la variabilidad motora para evaluar el rendimiento, ya que se encontró una variabilidad motora reducida en jugadores con mayor nivel de experiencia. La acción compensatoria de los segmentos corporales (especialmente en los golpes de fondo y en el antebrazo y la cabeza, donde los coeficientes de variación eran altos) debe estudiarse en profundidad porque puede ayudar en el diseño de tareas motoras, haciéndolas más específicas.

Palabras clave: MENS; deportes de raqueta; aprendizaje motor; flexibilidad motora; adaptación; rendimiento; coordinación motora; coeficiente de variación.

4.4.2. Abstract

Performance in tennis relies heavily on the skillful repetition of several types of tennis strokes, yet the role of motor variability has still received little scientific attention – especially at the within subject level. The present study aims to evaluate the role of motor variability depending on the strokes/body segment and the level of expertise. Thirty-five players performed a field test (including first and second serves, forehand and backhand strokes) with four synchronized gyroscopes placed on the trunk, head, upper arm and forearm. Variability was measured based on the coefficient of variation (CV) of the angular velocity peaks per stroke in each body segment. MANOVA revealed greater motor variability in the forehand and backhand than in the serve ($p < 0.001$), with head and forearm segments showing the highest variability (CV > 15 % in some cases). This result also translated to differences in variability between levels of expertise, with variability being greater among lower level players ($p < 0.02$ in all strokes, with Cohen $d > 1$ in some cases). Summarized, groundstrokes could imply more compensatory kinematic movements to keep the result of the action stable. Motor variability must be considered to evaluate performance, as a reduced motor variability was found in players with higher level of expertise. The compensatory action of the body segments (especially in groundstrokes and in the forearm and head, where the coefficients of variation were high) should be studied in depth because it can help design motor tasks, making them more specific.

Keywords: MEMS; racket sports; motor learning; motor flexibility, adaptability, performance, motor coordination, coefficient of variation.

4.4.3. Introduction

Tennis is a sport with a long history of biomechanics research. Tennis groundstrokes are ballistic nature techniques that require the coordination of multiple body segments (23). One of the main components of motor coordination is the movement variability, i.e., the trial-to-trial differences in body kinematics while performing a motor task (211). Variability in the execution of sports skills is important to the performance itself, for the development of skills, and in experimental research (212). The study of motor variability, as applied to sports actions, has been carried out by specialists in the area of motor control and, until recently, has been largely overlooked by sports biomechanics (213). Motor variability has traditionally been associated with motor noise generated in the central nervous system, creating a limiting factor to technical performance (214). *Dynamical systems theory* suggests that the organisation of the sensory-motor system implies the interaction of various constraints, such as the task, the environment and the organism, to produce movement. From this theory, it is apparent that variability in movement systems is omnipresent and unavoidable due to the distinct constraints that shape each individual's behaviour (214). In fact, the *theory of dynamic systems* differentiates between motor coordination variability and outcome variability. For this reason, in a goal-directed task, outcome variability in terms of the result of the action, is intended to be stable for optimal performance (244, 245). Motor coordination variability relates to the underlying movements, which must be modified according to the conditions of the environment (extrinsic factors such as wind or irregular ground) or alterations related to athlete self-reports (intrinsic factors such as perceived confidence or fatigue) (245, 246). In a similar line Davids et al. (214) indicate that motor coordination could have a compensatory function because variation of one execution parameter is compensated by changes in other movement parameters so that outcome variability can be minimized (218). Therefore, from a dynamical systems perspective, a higher level of technical performance requires a higher level of motor coordination variability and a lower level of outcome variability. In the case of tennis, motor variability has been studied mainly with respect to the serve (218–221), the forehand (27, 251), the variability in target accuracy (i.e. the way in which the ball bounces are distributed on the court) (41, 252) or how the variability of the racket's trajectory affects target accuracy (253, 254).

Differences in variability between strokes and between segments may reflect the mechanical idiosyncrasies of each type of stroke and the mechanical actions of the different segments. In other words, analysing motor variability in throwing tasks could aid to evaluate the action of different body segments and to study the coordination strategies used. Based on the *theory of dynamic systems*, this knowledge could reveal much about the strokes and segments where compensatory movements have special importance. Wagner et al., (226) analysed handball throws and found greater variability in the distal joint segments (associated with a compensatory function that may help to ensure suitable throwing), similar to what Button et al., (227) had found for basketball shooting (they suggested that compensatory motions of the elbow and wrist joint served to adapt to changes in release parameters of the ball). In tennis strokes, where high speed of the distal joints is reached and where subtle changes in racket trajectory could differentiate between successful and unsuccessful shots (224) it would be interesting to study the variability of the different body segments and compare the differences depending on the stroke. Despite all these investigations, there is very little research comparing motor variability between the three main tennis strokes, i.e., the forehand, the backhand and the serve.

The analysis of variability between player's levels of expertise can reveal important information about how skilled players satisfy situational constraints (227), helping us improve our understanding of motor coordination of complex movements (226). It could help in deciding whether to take variability as a variable related to performance, and not only the segmental contribution as normally done (177, 257). Wagner et al. (226) found a decrease in movement variability in highly skilled handball players and Lees and Rahnama (212) also suggest that highly skilled football players may be able to demonstrate less variability in the reproduction of a skill associated with a constrained task (e.g., kicking a ball to a target). On the contrary in basketball free-throws, Button et al. (227) found that improvement in skill level was associated with increased movement variability, and explained this founding based on the aforementioned *theory of dynamic systems*. Others have found that variability shows a *U-shaped* curve in relation to the skill level of the athlete (229) differentiating between random variability (present in novices) and active functional variability (that of expert players). In the particular case of tennis, movement variability is believed to negatively impact serve performance by reducing both speed and accuracy of the ball (219). However, Whiteside et al. (230) showed that increased motor variability did not reduce serve accuracy. Nevertheless, these studies analyse variability at the within-subject level and do not consider the level of play as an independent variable, so the relationship between motor variability and the level of expertise is not clear and should be studied further.

Following the above discussion, the present study aims to compare the intra-subject motor coordination variability of the main tennis strokes – i.e., groundstrokes and serves – by treating both the level of expertise and the body segment as independent variables. The hypothesis of the study is that mechanical differences between the different strokes and segmental actions will induce different values of variability (having higher values in the distal segments that will have a functional or compensatory function) and that the highest-level players will be those with the lowest motor coordination variability scores. Strengthening knowledge of the strokes and/or body segments that present the highest values of motor variability could improve the process of designing motor tasks. The results of the present research could also provide information on whether the kinematic variability allows differentiating between game levels, particularly in tennis.

4.4.4. Methods

Participants

A total of thirty-four tennis players of different ages and levels participated in this study. According to the International Tennis Number (105), 12 players could be classified as advanced (level 2-4 players; age = 27.8 ± 9; height = 180.3 ± 6.5; weight = 77.3 ± 7.7; body fat percentage = 12.9 ± 2.5; body mass index = 23.7 ± 1; skeletal muscle mass = 38.3 ± 3.8), 12 players as intermediate (level 5-6 players; age = 34.4 ± 9.4; height = 176.4 ± 5.9; weight = 77.9 ± 13.2; body fat percentage = 18.5 ± 8.5; body mass index = 25.1 ± 4.4; skeletal muscle mass = 35.7 ± 2.9) and 10 players as recreational (level 8 players; age = 27 ± 11.2; height = 177.9 ± 6.3; weight = 73.9 ± 10.9; body fat percentage = 17.6 ± 3.9; body mass index = 23.3 ± 2.5; skeletal muscle mass = 33.5 ± 4.2). Body composition was tested through bioimpedance (Inbody 230, Inbody, Seoul, Korea).

Inclusion criteria for the participants in this study were: (i) reporting normal vision and no history of any neuropsychological impairments that could affect the results of the experiment, (ii) not presenting any injuries during the previous two months, (iii) giving consent, and (iv) not having engaged in vigorous physical activity in the previous 48 hours.

The participants were informed about the main goals of the investigation and signed informed consent forms. Participants were informed that they could revoke the participation agreement at any time. The tennis players were treated according to the American Psychological Association (APA) guidelines, which ensured the anonymity of participants' responses. In addition, the study was conducted following the ethical principles of the

Declaration of Helsinki for human research and was approved by the local research ethics committee.

Procedures

Measurements were performed at the Sport and Health Research Institute (University of Granada). For each player, data was collected only once. To make sure that they met the inclusion criteria, each athlete completed a brief questionnaire on general aspects about history of injuries, rest and training. After that they performed the physical tests. A maximum of two players were scheduled per day.

Specific stroke performance test

In the present study motor coordination variability was assessed through multiple Nexgen triaxial IMU sensors (Nexgen Ergonomic I2M SXT, Montreal, Canada; size: 48.5 x 36.5 x 13.5 mm^3; weight: 22 g), which have been shown to be valid for analysing angular kinematics in tennis strokes by comparing them against a photogrammetric motion capture system (67). The study participants were fitted with four *Nexgen triaxial inertial sensors* (synchronized with each other, at a sampling frequency of 128 Hz) placed on the trunk, head, upper arm and forearm (67). The alignment of the local gyroscopes axes assumes the correct manufacturer axes alignment, as done in previous studies (67). As the aim was not to calculate joint angles, the axes between the different sensors were not aligned either physically or mathematically. The intention in the placement of the sensors was to align the gyroscope axes with the corresponding axes of each body segment. With the subject in anatomical position, one of the sensor axes was aligned with the longitudinal axis of the segment (the x-axis of the trunk, arm and forearm sensor and the z-axis of the head sensor), so that the acceleration value (observed on the real-time graph of the sensor recording software) was close to the value of 1G. The alignment of the other two local axes of the sensors with the anteroposterior and mediolateral direction of the segment, was done visually trying to align the sensor faces with the mediolateral and anteroposterior face of the segment (Figure 20).

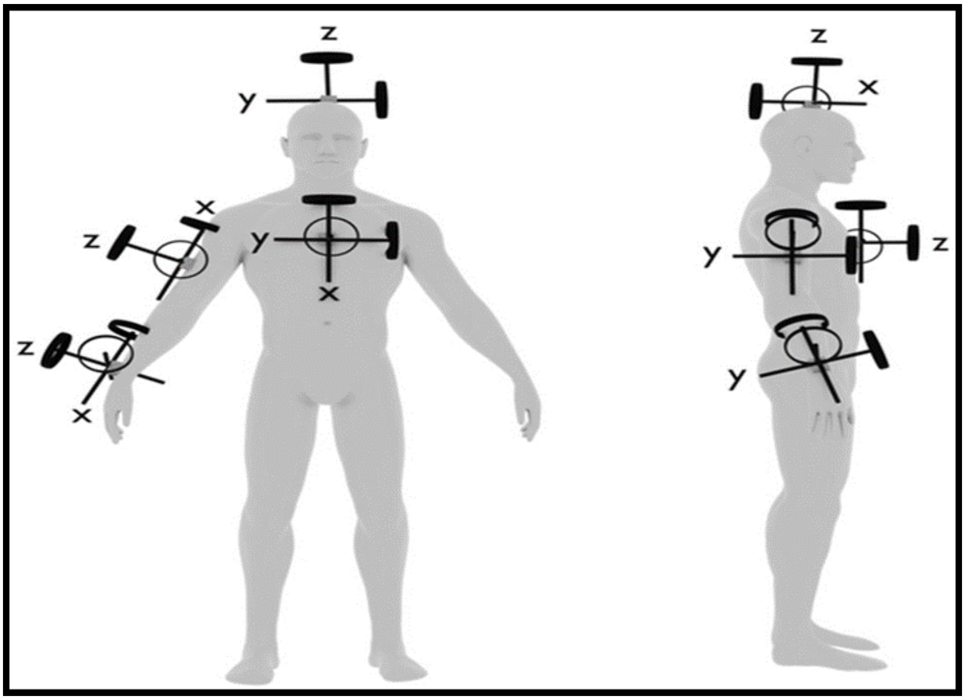


Figure 20. Sensor placement and axis directions

The specific stroke performance test was based on previous research (231). Before beginning the test, an eight-minute warm-up was performed, which consisted of joint mobility exercises and a five-minute rally (back and forth groundstrokes practice between two tennis players), two minutes from the service lines and three from the baselines, with the same expert trainer present at every test session. The stroke test was performed on a hard court with acrylic surface of type A (106) and each player used their own racket. A check of the tennis racket was carried out to ensure that they were in a good state and approved by the ITF (106). Also racket string tension was measured with a string tension meter (Tourna Stringmeter, Tourna, London, United Kingdom), to verify that all rackets had an adequate and similar tension. A correlation of 0.98 (Pearson r square) was reported between this device and a tensiometer ProsPro model MQT (ProsPro, Linz, Austria) (231). Finally, new balls were used (Wilson Pro Trainer, Wilson Sporting Goods, Chicago, United States) and they were changed every three participants.

All participants in the study performed a series of serves (including 10 first serves and 10 second serves) and two series of groundstrokes (including each series 10 forehands and 10 backhands, hitting both alternately). Therefore, per player there were 10 first serves, 10 second serves, 20 forehands and 20 backhands groundstrokes. This number of strokes was based on previous research analysing motor coordination variability of acyclic gestures (241, 261). The angular velocity peaks of each segment were evaluated for motor coordination variability, and the ball speed for outcome variability. Other studies analysing motor variability of sporting actions had also relied on the analysis of segment or joint angular velocities (216).

The ball speed was measured using a Stalker Pro II radar (Stalker Radar, Texas, USA), with an accuracy of ± 1 km/h according to the manufacturer. The stroke performance test was similar to previous studies using a ball throwing machine to standardize the trajectory of the approaching ball (233). Subjects were asked to hit as fast as possible while still maintaining the best accuracy values. Accuracy was analysed using the methodology of the study by Delgado et al. (67). In the case of the forehand and backhand series, two 2 x 2 m targets were placed (one in each corner of the court) and the shots were classified as Good Shots (%) when they entered the baseline rectangle but did not hit the target, Very Good Shots (%) when they hit the target or Out Shots (%) if the ball hit the net or did not enter the two aforementioned targets. In the case of service, the target was placed back in the service box and the shots were classified in the same way (the good shots were those that entered the service box) (Figure 21). Three minutes of rest was allowed between series to prevent any influence of fatigue.

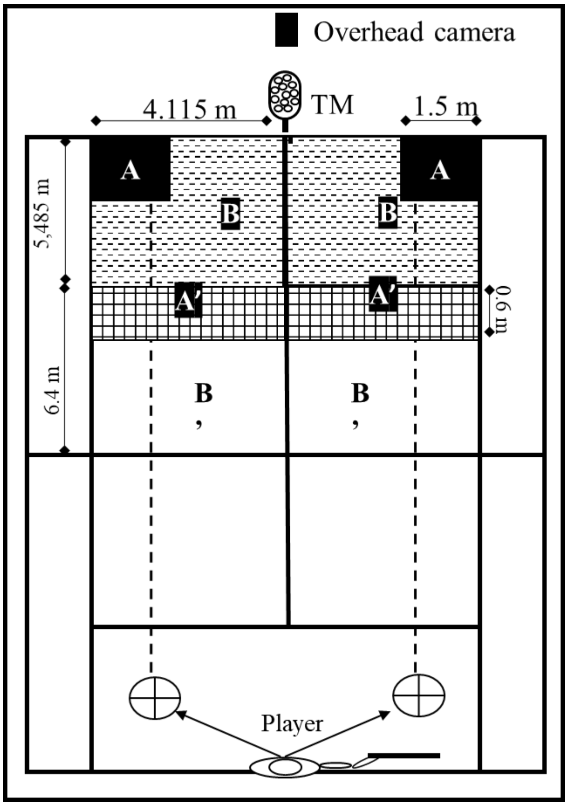


Figure 21. Diagram of the stroke test. The rectangle A and A' represent the areas of "Very Good Shots" (for the groundstrokes and for the service, respectively) and the B and B' rectangles represent the "Good shots" areas. *TM: Throwing machine

Analysis of the angular velocity signal

The IMU gyroscope sensor (prototype IDG-650 for the x- and y-axis and ISZ-650 for the z-axis, InvenSense, Sunnyvale, California, USA) has an integrated internal low pass filter and consequently very low white noise levels (67). Therefore, the untreated sensor output signals were used as done in other studies conducting variability analyses, expecting to obtain a more accurate representation of the variability within the system (263, 264). The OriginLab software was used to determine the angular velocity peaks corresponding to each stroke. Angular velocity peaks were selected in a spike pattern and close together, to ensure that the peak occurred during the stroke (See Figure 22 for more information). A description of the signals on each of the axes of the gyroscopes is described in the following lines. Firstly, we selected the angular velocity peaks largely due to the turning action of each segment along its longitudinal axis (trunk rotation, arm internal/external rotation or forearm pronation/supination movements) which above all corresponds to the angular velocity peak of the sensors of the trunk, upper arm and forearm on the x-axis (from now on referenced as: trunk-x, arm-x and forearm-x). They were negative on the serve and on the forehand, and positive on the backhand. The angular velocity peaks due to the rotation of the head along its longitudinal axis or angular velocity peaks of the head sensor on the z-axis (head-z) were also chosen. They were positive on the forehand and on the serve, and negative on the backhand. The angular velocity peaks related to adduction/abduction movements of the arm/forearm (arm-y and forearm-y) were positive on the serve and on the forehand, and negative on the backhand. Finally, the angular velocity peaks due to flexion/extension of the arm and forearm in a fundamental position (or arm-z and forearm-z) were selected. In the case of the arm, they were positive on the serve and on the forehand and negative on the backhand. In the forearm, they were positive on the forehand and negative on the serve and backhand.

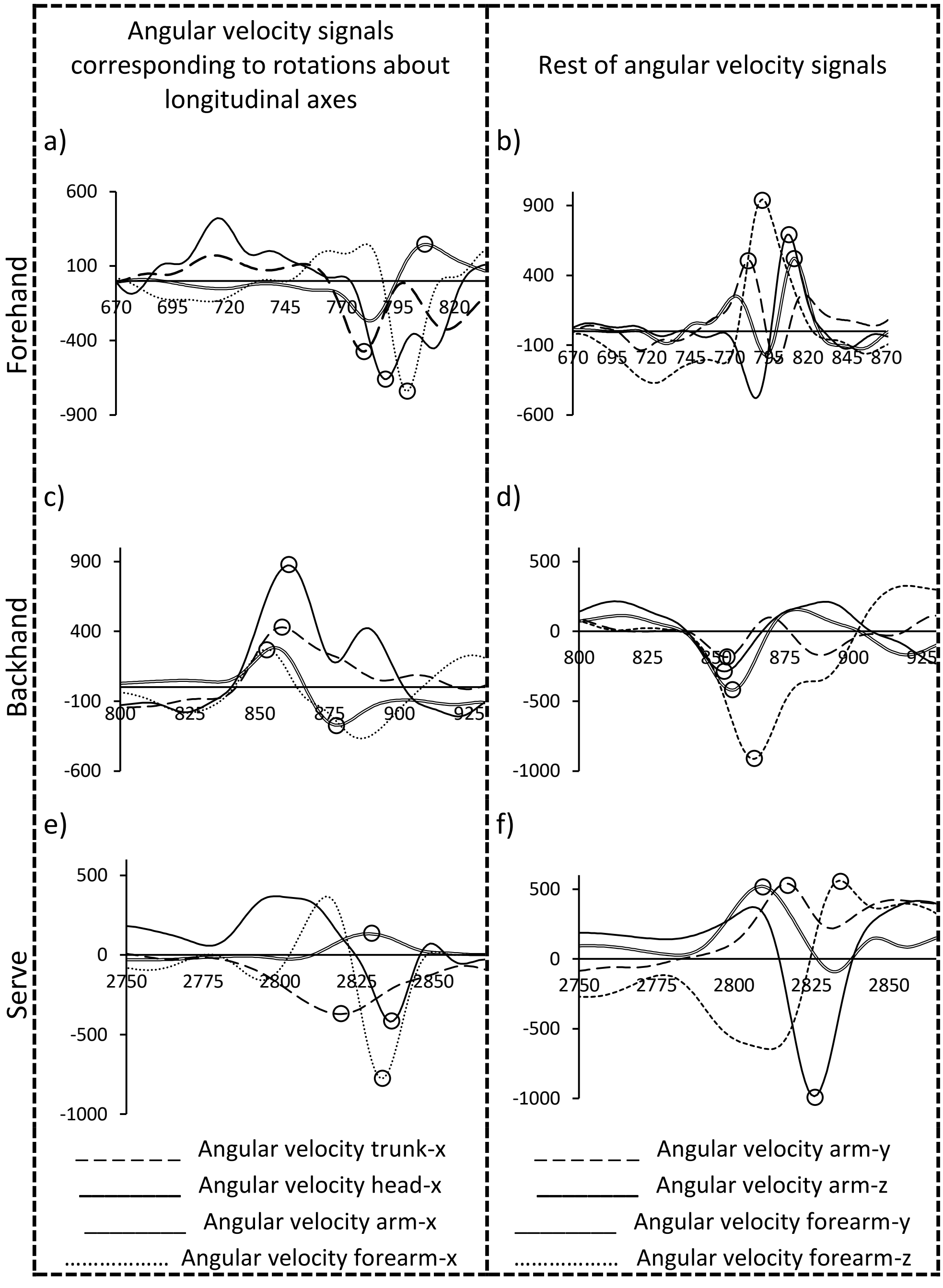


Figure 22. Angular velocity of the signals selected for forehand (a, b), backhand (c, d) and serve (e, f). Angular velocity peaks are indicated by a circle. The signals have been filtered (fourth order Butterworth filter with 6Hz cut-off frequency) only to improve visualization

Statistical analysis

The statistical analysis was carried out with the OriginLab software, with R and with the Real Statistic Using Excel tool (112).

As a measure of motor coordination variability, the coefficient of variation (CV) in percentage was used, by dividing the standard deviation by the mean and multiplying the result by 100. The use of the CV to assess motor coordination variability is common (241, 248, 261, 265). The average of the angular velocity peaks was also used as a descriptive parameter for the data. Prior to the calculation of means and CVs, outliers were removed with a conservative filter based on the median and the Median Absolute Deviation (MAD) (237). Those peaks whose magnitude was between the median and the MAD (237) multiplied by ± 5 were selected. The conservative value of five times the MAD was used to eliminate a small number of strokes.

To study the contribution of the selected variables on the ball speed, the partial correlation coefficients between each angular velocity variable and the ball speed were calculated and a multiple linear regression analysis was performed using the peaks of angular velocity as predictor variables and the ball speed as output variable. The quality of the correlations was assessed using the *Evans scale* (238)*,* which establishes the following levels: (i) 0.00-0.19, "very weak"; (ii) 0.20-0.39, "weak"; (iii) 0.40-0.59, "moderate"; (iv) 0.60-0.79, "strong"; (v) 0.80-1.0, "very strong". Variance inflation factors were also calculated to study possible multicollinearity problems. An inflation variance factor above 10 was selected to indicate multicollinearity problems.

To compare the motor coordination variability between the different strokes, a non-parametric repeated measurement MANOVA in R was performed using the Wild Bootstrap option and Tukey multivariate post-hoc comparisons (including the limits of agreement) (239), considering the type of stroke as independent variable and the coefficients of variation of the angular velocity peaks as dependent variable. This process is clarified in Figure 23. MANOVA takes into account the covariance structure of the variables included in the model, allows to detect multivariate response patterns, and decreases the probability of rejecting a true null hypothesis (type I error). In addition, repeated measure ANOVAs were made to study the differences between strokes in each of the angular velocity peaks analysed. In this case the post-hoc analysis was carried out using the Tukey's Honest Significant Difference (HSD) test. The effect size (Cohen d) was provided by the Real Statistic Using Excel software. To interpret the magnitude of the effect size we adopted the following criteria: (i) 0-0.20, “negligible effect”; (ii) 0.20-0.50, “small effect”; (iii) 0.50-0.80, “medium effect”; (iv) 0.80-1, “large effect”.

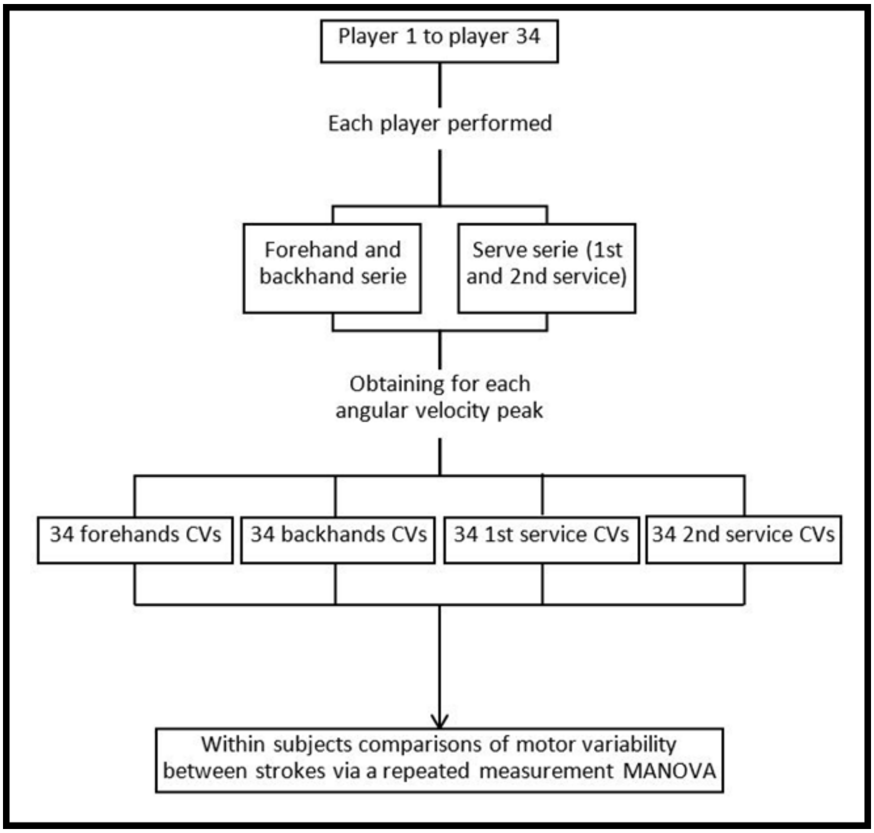


Figure 23. Schematic overview of the statistical procedure to perform the repeated measures MANOVA

To compare the total first serve, second serve, forehand and backhand variability depending on the level of expertise, a one factor ANOVA per stroke was performed, using a single measure of variability per stroke (the mean of the CV of each segment). Tukey HSD was used to carry out for the post-hoc analyses (computing the effect size using the Cohen d).

Considering the number of comparisons performed by statistical test the significant p value was established at $p < 0.05$ in the case of the: (i) MANOVA (and corresponding post-hoc analysis), (ii) regressions and (iii) ANOVA (and post-hoc analysis) performed to compare variability according to the levels of expertise. In the case of the repeated measures ANOVA and in the corresponding post-hoc analysis, the p-value was set at 0.001, taking into account the number of comparisons made (32 in total), to reduce the probability of committing type I errors (applying Bonferroni correction, i.e., dividing the p value 0.05 by 32). This selective approach to the value of significant alpha has been previously conducted in sport science studies (240).

4.4.5. Results

Few outliers per stroke and per variable were eliminated from the study data. In the case of serves, 100% of the angular velocity peaks were included in the data set. In the case of forehand, more than 19 of 20 angular velocity peaks per player and per segment were included (19.6 ± 0.41 peaks). In one of the players only 17 peaks were included for head-x. In the backhand, something similar occurred and in all cases more than 18 angular velocity peaks were included per player (19.7 ± 0.6), except for one player in which only 17 angular velocity peaks for trunk-x were retained.

The percentage of O*ut Shots*, G*ood Shots* and *Very Good Shots* was 55 ± 20 %, 8 ± 9 % and 38 ± 19 % for the first serve, and 42 ± 23 %, 6 ± 11 % and 51 ± 23 % for the second serve, respectively. Percentages for forehand were 42 ± 15 %, 39 ± 14 % and 19 ± 12 %, and for backhand they were 40 ± 16 %, 45 ± 15 % and 15 ± 10 %. Average ball speeds were 134 km/h, 111 km/h; 101 km/h and 91 km/h for the first serve, second serve, forehand and backhand, respectively. The speed CVs were 6 %, 8 %, 11 % and 10 %, respectively. The averages and CV averages for the peak segment angular velocities are shown in Table 11.

Table 11. Averages (CV averages [%]) of angular velocity peaks (degrees/second) and partial Pearson's correlation coefficients with the ball speed

Variable	Stroke							
	1st serve		2nd serve		Forehand		Backhand	
	Average (CV)	r	Average (CV)	r	Average (CV)	r	Average (CV)	r
Trunk-x	613 (6.7)	0.56	533 (7.7)	0.5	625 (11.3)	0.74	602 (12.8)	0.39
Arm-x	1295 (13.7)	0.61	1071 (14.9)	0.51	802 (14.9)	0.41	882 (13.4)	0.66
Arm -y	894 (7.3)	0.39	808 (9.5)	0.46	504 (13.5)	0.23	642 (13.5)	0.57
Arm -z	590 (11.6)	0.4	539 (12.2)	0.28	550 (13.8)	0.2	413 (15.8)	-0.06
forearm -x	1467 (15.2)	0.61	1255 (15)	0.54	1049 (22.7)	-0.09	808 (14.7)	-0.01
forearm -y	1049 (7)	0.43	945 (7.2)	0.53	1008 (7.1)	0.43	940 (10.2)	0.61
forearm -z	1432 (5.7)	0.74	1278 (7)	0.62	613 (21.5)	0.41	647 (12.6)	-0.19
Head-z	332 (12.6)	0.53	332 (11.1)	0.51	138 (25.4)	0.29	183 (18.7)	0.34

As for the partial correlations between the measurements of angular velocity and stroke speeds (Table 11), strong correlations were found on the first serve, for the arm-x, forearm-x and forearm-z; on the second serve for the forearm-z; on the forehand for the trunk-x and on the backhand for the arm-x and forearm-y. To graphically demonstrate the association of the angular velocity measurements and stroke speeds, some examples of the partial regression lines, corresponding to the indicated correlations, are shown in Figure 24. Moderate correlations were also frequent. Multiple linear regression models explained the ball speed variance by 62% ($p < 0.001$; $F = 7.72$), 47% ($p < 0.001$; $F = 4.64$), 62% ($p < 0.001$; $F = 7.70$) and 44% ($p = 0.002$; $F = 4.21$) for first serve, second serve, forehand and backhand (Figure 25). The average of the variance inflation factors for the multiple linear regression model for the first serve was 2.8 (the maximum was 5.7), 3.0 for the second serve (maximum 6.4), 1.6 for the forehand (maximum 2.1) and 2.4 for the backhand (maximum 5) indicating that multicollinearity was not a concern.

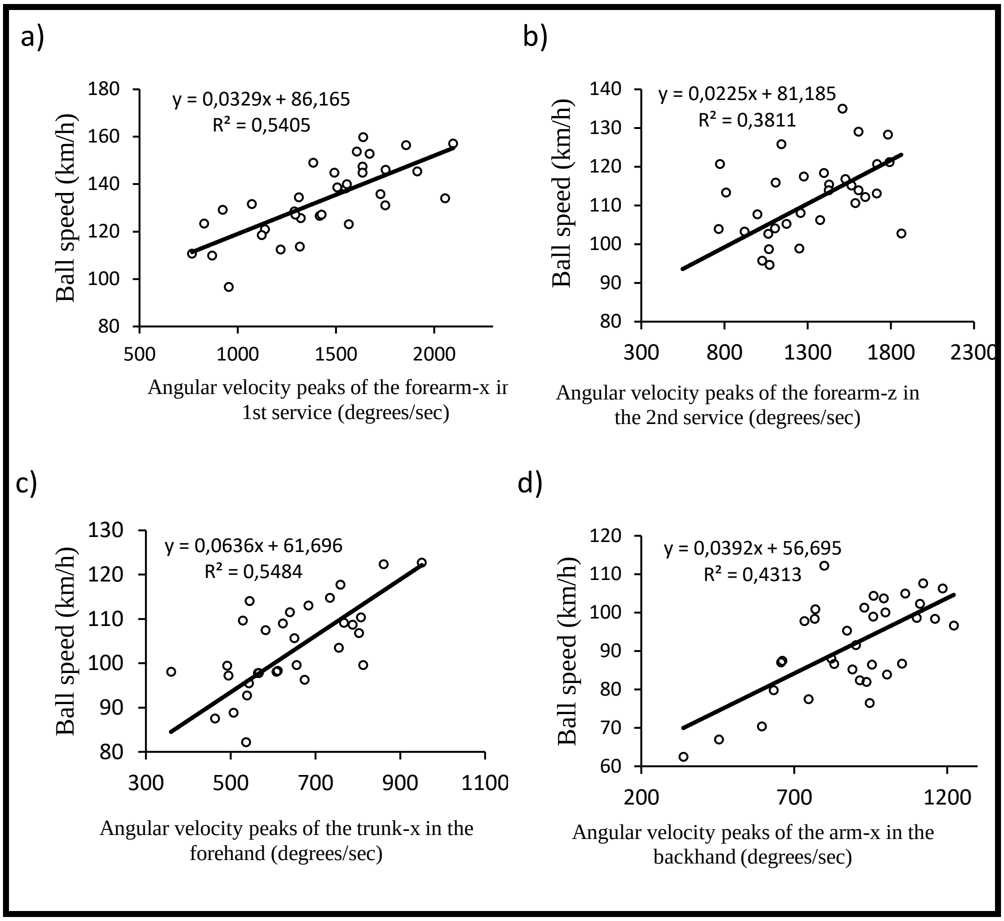


Figure 24. Regression lines of the best fit between some angular velocity peaks (means of all subjects analysed) and the ball speed. These are specifically the regression lines for forearm-x and forearm-y in the case of the first and second serves (a, b), for trunk-x in the case of the forehand (c) and for arm-x in the case of the backhand (d)

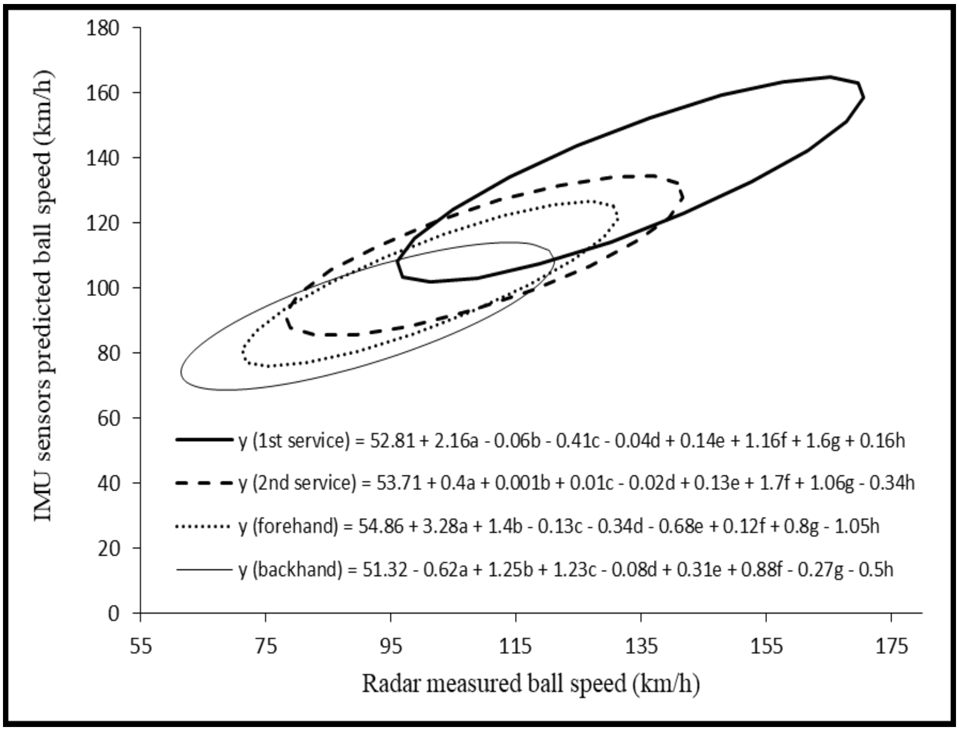


Figure 25. 95% confidence ellipses containing the predicted values of the ball speed regression versus the measured values of the ball speed (km/h). The multiple linear equation with the intercepts and the slope values are included ((a-h) being the values of angular velocity in degrees/s of the trunk-x, arm-x, arm-y, arm-z, forearm-x, forearm-y, forearm-z and head-z, respectively)

The non-parametric repeated measurement MANOVA showed significant differences in motor coordination variability between the different strokes (Wald-Type statistic = 274,653; degrees of freedom = 24; $p < 0.001$). Multivariate post-hoc comparisons showed lower values of variability in the first serve than in the forehand ($p < 0.001$; estimate = 50.51; lower limit = 21.13; upper limit = 79.88) and lower values for the second serve with respect to the forehand ($p < 0.001$; estimate = 45.56; lower limit = 15.77; upper limit = 75.35). There were also significant differences in the comparison between the first serve and the backhand and between the second serve and the backhand, with the variability in the backhand being greater in both cases (p

= 0.007; estimate = 32.18; lower limit = 5.7; upper limit = 58.66 and p = 0.044; estimate = 27.24; lower limit = 0.3; upper limit = 54.18, respectively).

The ANOVAS of repeated measurements showed differences between strokes in motor variability ($p < 0.001$ in all cases) for the: (i) trunk-x (first serve CVs < forehand and backhand CVs; second serve CVs < backhand CVs); (ii) forearm-x (first serve, second serve and backhand CVs < forehand CVs); (iii) forearm-z (first serve CVs < forehand and backhand CVs; second serve CVs < backhand CVs; backhand CVs < forehand CVs) and (iv) head-z (first serve, second serve and backhand CVs < forehand CVs; second serve CVs < backhand CVs). There were no differences in the motor variability between strokes for the arm-x, arm-y, arm-z and forearm-y.

Finally, there were significant differences ($p < 0.05$ in all cases) in the variability scores between the three levels of expertise for each of the strokes analysed (Figure 26). In the case of the first serve and second serve there were differences between the advanced players and the recreational players and between the intermediate players and the recreational players, the variability being lower in the more skilled players in both cases (Figure 27). In the case of the forehand, advanced players also obtained significantly lower values of variability than the intermediate players and the recreational players (Figure 26). In the backhand there were only differences between the advanced players and the recreational players, with variability being significantly lower in the first group (Figure 26).

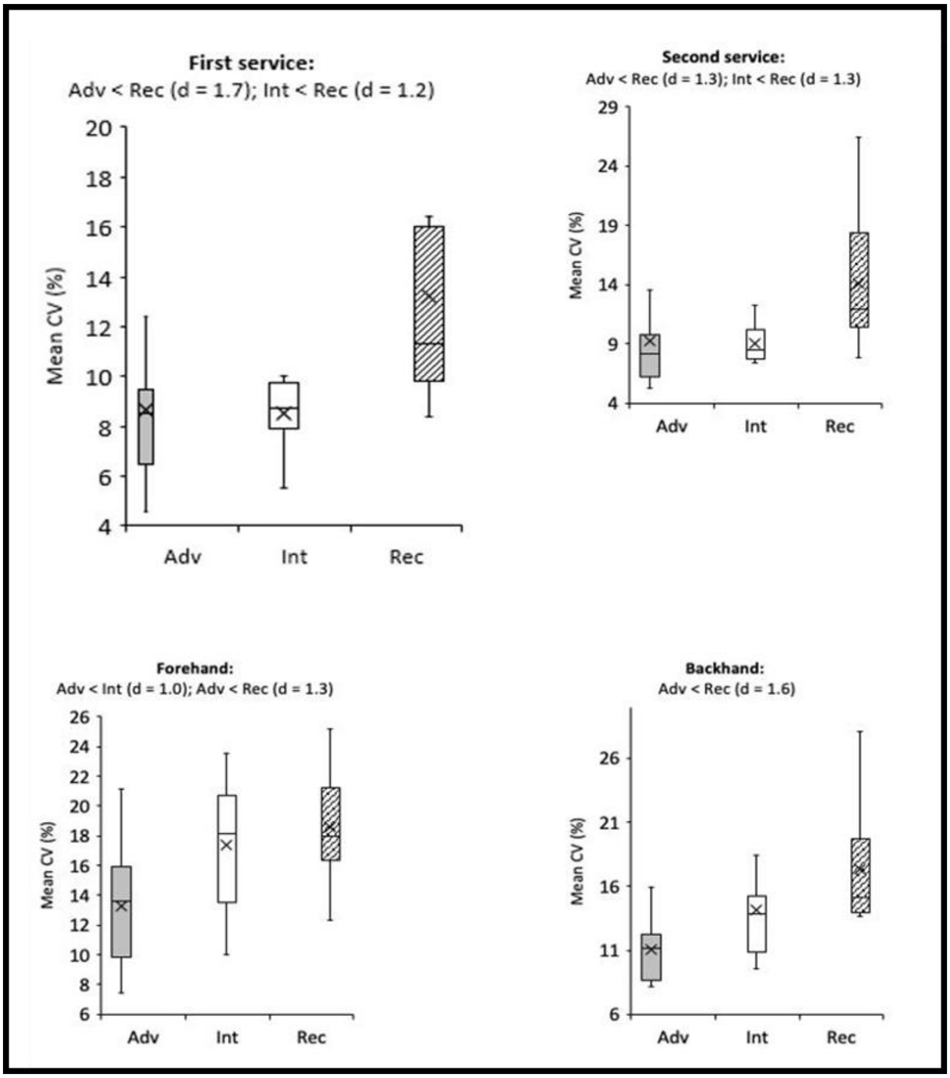


Figure 26. Variability differences between level of expertise in each stroke analysed. Significant differences and effect sizes (Cohen d values) are indicated in the title of each graph. *Adv: Advanced players; * Int: Intermediate players; *Rec: Recreational players

4.4.6. Discussion

For as far as we are aware, our study was the first to assess motor coordination variability across the most common tennis strokes in players of recreational to advanced levels. Partial correlations and multiple linear regressions indicated that the selected variables were important for the variance of the ball speed. The MANOVA and ANOVAS of repeated measurements showed a greater variability in the forehand and backhand strokes than in the serves, with greater variability scores in the distal segment (i.e., the forearm) and in the head. There were also differences in motor coordination variability between the advanced, intermediate and recreational players, in all strokes analysed, with variability being lower in the more skilled groups. The difference in motor variability between the main strokes and body segments should be taken into account in the design of future tennis drills, as will be further discussed in this section. Also motor variability could serve to differentiate between levels of expertise (lower motor variability indicating a higher level of expertise).

The CVs reported in this study for the different strokes ranged from approximately 5% to 25%. These data are very similar to those of other studies that analysed ballistic gestures with high precision requirements (241, 250, 265, 270). In the case of the tennis serve, for example, the coefficients of variation of the humerothoracic joint kinematics reported by Sevrez et al. (221) ranged between 2% and 20% (reaching a CV of 37.2 % for the flexo/extension movement in the cocking phase). In table tennis, the CV in the contact and follow-through phase of the shoulder and elbow kinematics for the topspin forehand were a little higher than in the present research (>

30% in the contact phase and >20% in the follow-through phase) but they studied the joint angle and not the angular speed (242).

The kinematic comparison and motor variability of the different strokes has not often been studied (most studies have analysed the kinematics of the strokes in isolation) and it is very difficult to find studies that allow one to make a comparison between the different strokes. In the present study CVs were greater in the groundstrokes than in the serves, this may be due to the fact that in the forehand and backhand stroke the ball was thrown by a ball throwing machine introducing more sources of variability, such as the trajectory the ball follows in the air, the bounce of the ball (determined in part by the physical characteristics of each ball) or the movement of the player towards the ball. In the case of the serve, the player is in a more static situation, the ball is thrown by the subject himself, there is no bounce of the ball on the ground and the path is more predictable, thus eliminating possible sources of variability. In support of this hypothesis Ilmane and LaRue suggest that the complexity of an oriented-goal task depends on the differences in the temporal constraint of each task (these authors analysed the handball throwing) (243). In simple terms, motor variability is affected by time constraints. Generally, it is more complex to perform a groundstroke where the player does not decide when to initiate movement, than a self-initiated stroke, such as a tennis serve (243). In the groundstrokes, the player has to adjust the posture and the displacements of the body segments in relation to the changing position of the ball, so the subjects modify their behaviour during the throw in each trial. In the self-initiated throw the player determines the start of the movement reducing the complexity of the human-environment system (243).

The highest values for the CVs were found in the forehand on the forearm-x, forearm-z and head-z (they were 22.7 %, 21.5 % and 25.4 %). In the case of the backhand, the head-z rotation also obtained a high value for the CV (18.7 %). Taking into account that strokes with more topspin imply a greater pronation of the forearm than a flat forehand (37), it is hypothesized that the high variability values over the forearm-x and forearm-z are related with the differences in the topspin between strokes at a within subject level. Players typically modify the topspin effect between strokes in the same series, to change the ball trajectory and correct the long or short errors, which could affect variability values. In other words, it is possible for players to alternate between strokes with more or less spin effect, to try to maintain high accuracy thus increasing variability. Another source of variability on the forearm-x could be the unwanted rotations over the longitudinal axis of the racket produced by off-centre impacts. In this line Kentel et al. (244) suggested that the location of the ball impact on the racket strings affects the kinematics of the racket and arm, and an off-centre stroke on the longitudinal axis of the racket could create a moment of force that would cause the racket to turn on this axis and thus rotate the forearm on its longitudinal axis. Wagner et al. (226) and Button et al. (227) also found an increase in movement variability in the distal joint movements during the acceleration phase of throwing actions and suggested that this is due to compensatory movements in this segment (they called it functional variability or compensatory coordination).

As far as the head-z is concerned, the great variability found in forehand and backhand is probably due to the turns of the neck on its longitudinal axis produced during these strokes. Although it has been little studied in the case of tennis, the movements of this segment are a subject of interest to expert coaches, as the gaze fixation is related with the stabilization of the rest of the body during the execution of the stroke or with the need to extract operational information from the ball (245). In other sports, such as baseball or basketball where accuracy is also an important factor, head and gaze-tracking strategies among players with different skill levels have been studied in depth, and seem to have a strong influence on shooting success (246–248). In tennis, Lafont et al. (245) revealed that elite players show a characteristic fixation of the gaze in the direction of the contact zone on impact and during the follow-through of the stroke.

Lower motor variability in a closed task (such as those in this study) is indicative of a higher level of technical execution (241, 248, 256). Along this line, Wagner et al. (226) found that there was a decrease in movement variability in highly skilled and moderately skilled handball players. In studies related to golf swings (216) and baseball pitches (249), variability of selected kinematic parameters also decreased from unskilled to skilled athletes. In the case of the present work, motor variability was lower in the more skilled players in the four strokes analysed, which could be due to a more consistent and regulated performance (226). On the contrary in basketball free-throws, improvement in skill level was associated with increased movement variability (227). Consequently, we believe that more studies of this kind should be carried out in tennis, including players from a wide variety of playing levels (i.e., novice players and international players). The results of the present study also suggest considering motor variability as a measure of kinematic performance, and not only the segmental contribution to ball speed or accuracy as is commonly done (177, 257) In this regard, motor variability has been included as a measure of performance in the evaluation of other ballistic nature skills (250).

The results of this work suggest that there are differences in motor strategies depending on the type of stroke/segment and could allow us to improve the design of training tasks. As an example, by improving the adaptability of stroke/segments, which are thought to exhibit greater compensatory motor variability. The function of these segments is to correct the action to keep the outcome stable, i.e., to hit with the appropriate speed and direction. One exercise that could improve the compensatory motor variability in groundstrokes (that showed the highest values of motor variability), is playing with heterogeneous balls with different bounce characteristics, which may force the player to correct the position of the arm/head in a short period of time. Also playing in different surfaces could avoid an adoption of excessively consistent and unadaptable stroke patterns.

To reduce the complexity of the motor task and to control undesirable sources of variability, the present study analyses motor variability under relatively stable environmental conditions. Considering that there are few studies of variability between different strokes in the case of racket sports, it is essential that the first investigations are carried out under simple conditions. Variability could be assessed under more controlled conditions by eliminating possible sources of variability such as player displacements or ball trajectory (using a ball fixed on a flexible stick) and analysing the differences against less controlled conditions, to see the effects of these sources of variability. Future studies should also analyse motor variability in the case of tennis in less constrained situations, including more complex decision-making tasks than in the present work. Considering that the phase of the movement and the characteristics and speed affect motor variability – in throwing tasks, distal segments of the kinematic chain in the final stages have shown higher variability according to Wagner et al. (226) future research should analyse motor variability performing a phasic analysis (e.g., backswing, forward swing, and follow-through). The main strength of this work is that it aimed to study the variability in different tennis strokes in an on-court situation, something that has rarely been done to date.

4.4.7. Conclusion

In this study with a heterogeneous sample of tennis players executing strokes in a controlled situation, groundstrokes, less skilled players and sensors on the forearm and head, showed the highest values of motor variability. Higher motor variability values for groundstrokes than for serves are explained by the differences in time constraints and external sources of variability, such as ball trajectory. As for differences between body segments, future studies should analyse this finding in greater depth, considering the compensatory role of motor variability. Because there were differences in motor variability depending on the level, the use of variability outcomes in performance-oriented tests is recommended, as it is done in other ballistic nature skills.

DESARROLLO TECNOLÓGICO: APLICACIÓN BASADA EN EL ASESOR VIRTUAL DE TENIS (portada)

4.5. DESARROLLO TECNOLÓGICO: APLICACIÓN BASADA EN EL ASESOR VIRTUAL DE TENIS

Desde la cuenta para desarrolladores del Human Lab (humanlab@ugr.es) se llevó a cabo el registro y publicación en el Play Store de la aplicación a la que se llamó *"Virtual Tennis Coach"*. Con el motor gráfico Unity®, se generó el Android App Bundle, que posteriormente se subió a Google Play Console para compilar los diferentes archivos APK disponibles en el Play Store. El desarrollo de la aplicación se realizó de forma paralela con el proyecto de la Junta de Andalucía ACTIVITAL® (Ref. EXP_74829), aprovechando así sus procesos, desarrollos y bases de datos. De forma resumida, se desarrolla a continuación: ¿Qué es ActiVital?, ¿A quién va dirigida? Y ¿Qué pretende conseguir? Con el objetivo de que el lector entienda el verdadero potencial que podría llegar a alcanzar "Virtual Tennis Coach" en futuras versiones de actualización.

ActiVital® es una plataforma digital desarrollada por un equipo multidisciplinar de investigadores y tecnólogos de la Universidad de Granada, vinculados al iMUDS. Dicha plataforma digital permite diseñar planificaciones basadas en deporte saludable, actividad física y ejercicio físico. Además, admite la supervisión de los resultados, introduciendo herramientas de monitorización individual y grupal de los programas de ejercicio físico desarrollados. Todo ello de forma accesible y online, utilizando herramientas informáticas integradas en navegadores web y apps (figura 27).

Figura 27. Captura de pantalla de la app de ActiVital® donde se puede observar un ejemplo de ejercicio incluido en una sesión de entrenamiento

ActiVital® está dirigida a cuatro perfiles: en primer lugar, a expertos en planificación y diseño de ejercicio físico saludable y deporte. En la plataforma se llamarán educadores físico-deportivos; en segundo lugar, se encuentran los expertos en evaluación y supervisión de indicadores de salud y condición física (asesor de salud: médicos, enfermeros y profesionales de ciencias del deporte); en tercer lugar, se enfoca para Instituciones del sector público y privado vinculadas al sistema deportivo y/o socio-sanitario (instituciones y gestores: consejerías, diputaciones provinciales, ayuntamientos, federaciones deportivas, clubes, etc.); en cuarto lugar, los usuarios finales de la plataforma (personas usuarias) que proceden de los distintos grupos poblacionales con perfiles marcados por el Servicio Andaluz de Sanidad (SAS) de cualquier rango de edad. La aplicación desarrollada en la presente tesis *"Virtual Tennis Coach"* añade a lo anterior ejercicios específicos de tenis encaminados a optimizar su aprendizaje en todos los niveles y edades.

ActiVital® tiene como objetivo principal proporcionar una plataforma integral que permita a los educadores físico-deportivos diseñar y seguir programas de ejercicio personalizados. Esta plataforma busca mejorar la condición física, la salud general y el bienestar de los usuarios. A través de herramientas informáticas avanzadas, los educadores físico-deportivos podrán acceder a una amplia base de datos de ejercicios y sesiones, recibir orientación virtual de expertos y realizar un seguimiento detallado de su progreso. El objetivo es asesorar a las personas para que tomen el control de su salud y alcancen sus metas de forma segura y efectiva. ActiVital® permite fácil acceso a una base de datos de ejercicios (más de 3000) y sesiones (circuitos, juegos, baile, aerobic, fuerza, movilidad, coordinación, etc.). El punto innovador se adquiere durante la realización de las sesiones ya que incluyen:

- Herramientas tradicionales basadas en texto, infografías estáticas y grabaciones de audio.
- Grabaciones de los ejercicios en vídeo.
- Ejercicios ejemplificados por **avatares 3D animados**.

En *"Virtual Tennis Coach"* se provechan algunas de las funcionalidades de ActiVital®, pero eliminando el enfoque sanitario ya que su objetivo es optimizar el proceso de aprendizaje y perfeccionamiento de la técnica en tenis. Por lo tanto, *"Virtual Tennis Coach"* supondrá una "INSTITUCIÓN" y "PROYECTO" aparte de ActiVital®, sin embargo, manteniendo la base de datos de ejercicios (para sesiones de preparación física de tenis) y la estrategia de aprendizaje basada en asesores 3D animados. En la figura 28, se puede observar el entrenador virtual creado de forma específica para la aplicación de esta tesis *"Virtual Tennis Coach",* cuya apariencia se basa en el autor.

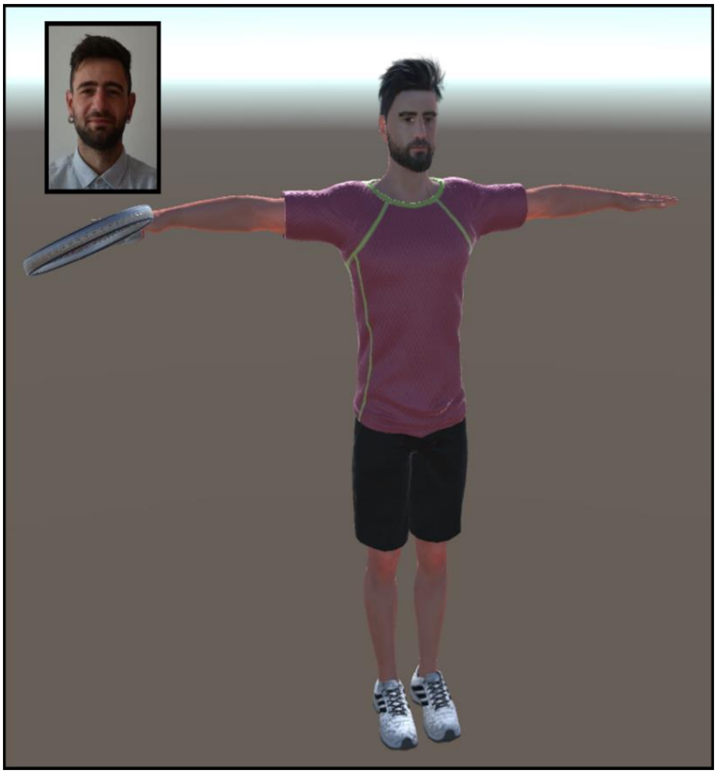


Figura 28. Asesor virtual de la aplicación *"Virtual Tennis Coach"* en posición anatómica

La figura 29 muestra el entorno de la aplicación *"Virtual Tennis Coach"* que incluye dos pistas de tenis con sus respectivos complementos (focos, carro de pelotas, raquetas, zonas de descanso para los jugadores, etc.). Dichos diseños 3D se adquirieron en Unity Asset Store y se adaptaron a las necesidades específicas de la aplicación.

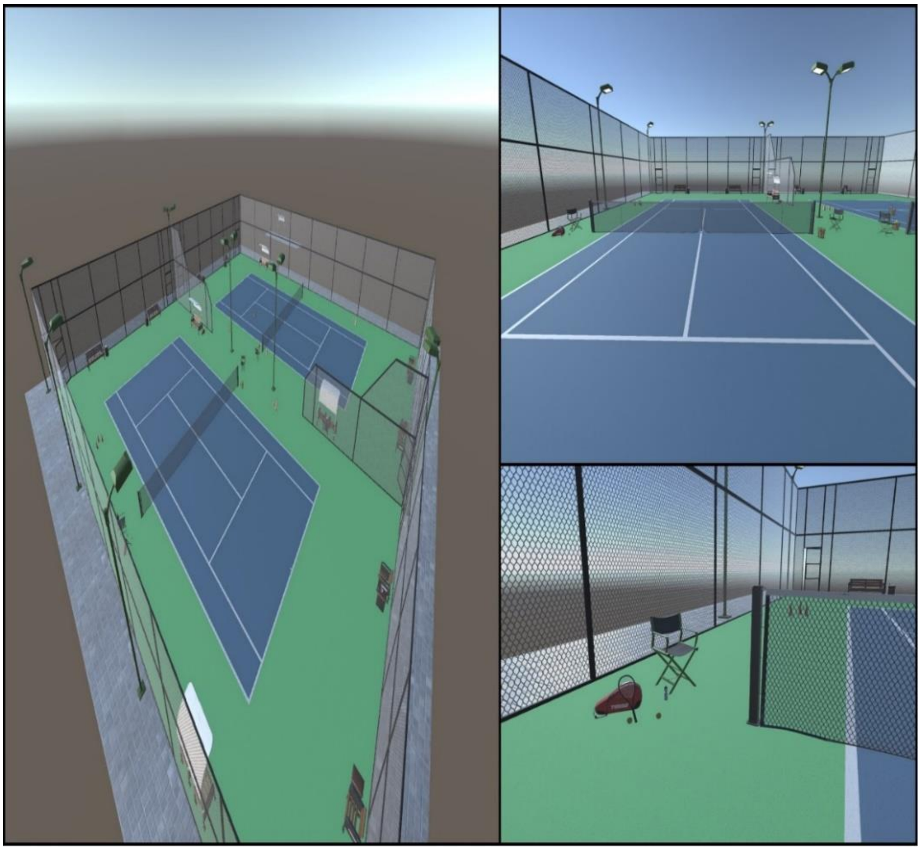


Figura 29. Entorno 3D de la aplicación *“Virtual Tennis Coach”*

En las figuras 30, 31 y 32 se puede observar al asesor virtual ya insertado en el entorno realizando distintos tipos de golpeo. En el caso de la figura 31 el asesor virtual se encuentra efectuando un revés a una mano, capturado desde dos perspectivas distintas, en la figura 32 realizando un saque cortado y, por último, en la figura 33 ejecutando una volea de derecha. En las siguientes figuras se puede apreciar cómo se han insertado las siguientes funcionalidades a la aplicación: pausar y reanudar en el momento deseado; rotar, acercar y alejar la cámara; despegable para seleccionar el tipo de goleo que queremos que realice el asesor.

Figura 30. Capturas del asesor virtual realizando revés a una mano

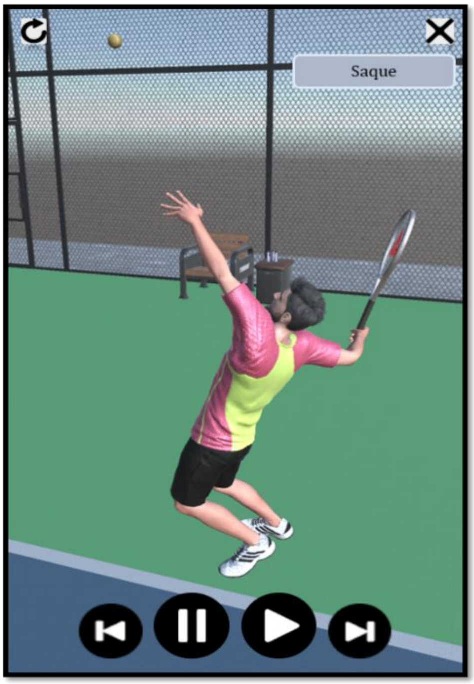


Figura 31. Asesor virtual realizando un saque cortado

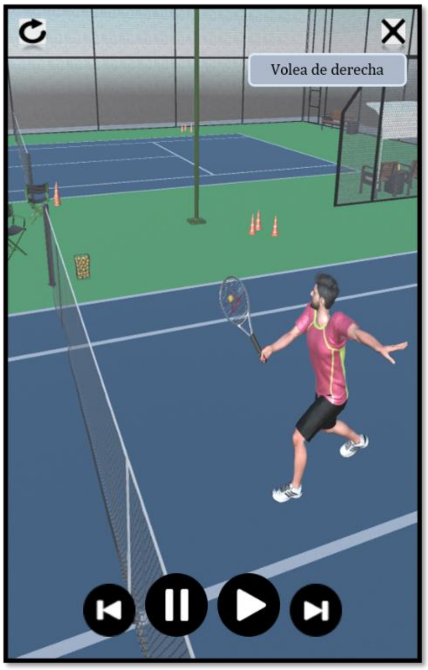
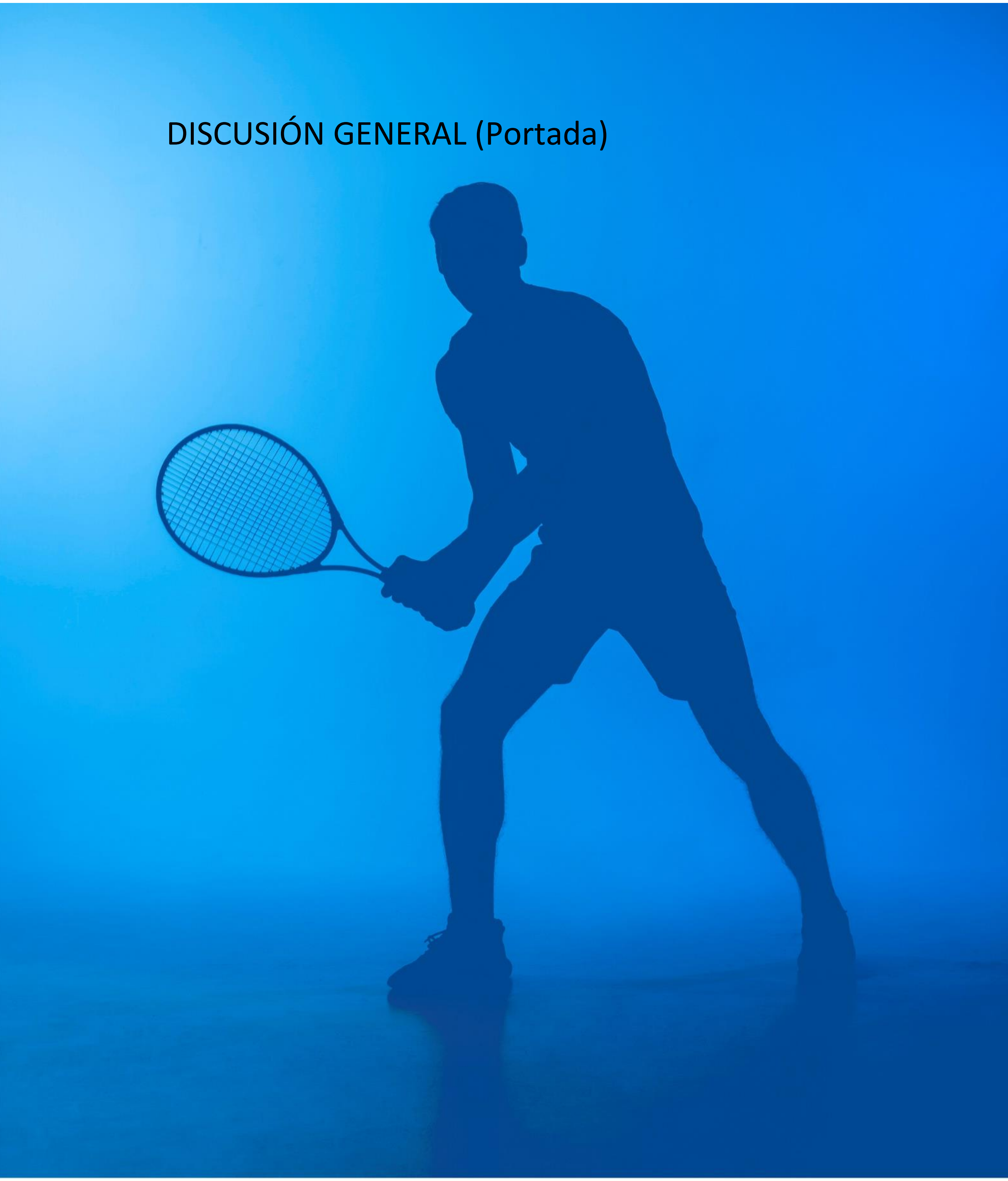


Figura 32. Asesor virtual ejecutando una volea de derecha en la red

DISCUSIÓN GENERAL (Portada)



5. DISCUSIÓN GENERAL

La presente tesis doctoral tuvo como objetivos incrementar el conocimiento existente sobre la validez, fiabilidad y formas de aplicación de las nuevas tecnologías portables para la monitorización de parámetros biomecánicos, fisiológicos y de rendimiento en tenistas de distintas edades y niveles de juego. Para ello, se llevaron a cabo cuatro estudios y un desarrollo tecnológico: se comenzó con la validación de tecnologías *(estudios 1 y 2)*; posteriormente, se utilizaron las tecnologías portables en estudios de campo *(estudios 3 y 4)*; y finalmente, se desarrolló un asesor virtual de tenis para Android *(Véase las discusiones específicas de cada estudio para mayor profundidad de análisis de las distintas variables trabajadas).*

A pesar de que en España existen una preferencia por disciplinas deportivas como el futbol o el baloncesto (251), en Granada el 25 % del alumnado que realiza deporte extraescolar se decanta por una disciplinada de deportes de raqueta (6). Dentro de los distintos tipos de deportes raqueta los más practicados son pádel y tenis, en este orden, lo cual coincide con los estudios previos de la bibliografía (6, 252). Los datos anteriores hacen de la zona evaluada un lugar idóneo para la futura implementación de la aplicación basada en asesores virtuales *(véase apartado de líneas futuras)*.

Los *estudios 1 y 2* son estudios de validación de tecnologías wearables. En ambos, se concluye la validez y fiabilidad de los dispositivos en función de los resultados obtenidos. Lo que demuestra que las nuevas tecnologías portables están superando sus carencias tradicionales, tales como los movimientos de la piel que dificultan su desempeño, las interferencias provocadas por campos electromagnético, las menores frecuencias de muestreo que llegan a alcanzar o los distintos métodos de calibración (62, 185, 209, 281). Por añadido, la labor de este tipo de tecnologías en tenis se dificulta aún más, ya que es un deporte muy explosivo donde el antebrazo llega a superar las 2000 rotaciones por segundo momentos antes del impacto con la pelota (63, 80). A pesar de la confirmación de la validez y fiabilidad de los dos wearables evaluados en la presente tesis, la comunidad científica no debe confiarse y utilizar de forma aplicada cualquier wearable sin su correspondiente validación previa, ya que puede llevar a aumentar el riesgo de lesión del deportista o que se tomen decisiones equivocadas en su planificación deportiva (94). Además, existen casos en los que tras evaluar la calidad del dato que aporta el dispositivo, encontramos grados de acuerdo muy bajos o nulos respecto al sistema de referencia, como ocurrió en el recientemente publicado artículo de Ruiz-Malagón et al., (254) donde se concluye que el dispositivo evaluado no presenta validez midiendo cinemática pélvica durante carrera sobre tapiz.

En cuanto a los *estudios 3 y 4,* en ambos, se utilizó una adaptación del Loughborough Tennis Test (107) y se aplicaron tecnologías wearables (IMUs) previamente validadas en la bibliografía, con el objetivo de obtener conclusiones de valor biomecánico dentro del tenis. En el *estudio 3,* se analizaron las diferencias cinemáticas de tren superior entre los tipos de revés SH y DH mediante el uso de giróscopos y en el *estudio 4* se evaluó cómo influye la variabilidad motora en el rendimiento de los principales golpeos de tenis en función del segmento corporal y el nivel de juego del tenista, también mediante IMUs. El *estudio 3* demuestra que los dispositivos IMUs permiten analizar la cinemática (angulaciones articulares, CI, o ω_{peak}) del tenista con un grado de precisión similar al obtenido con los tradicionales métodos de captura de movimiento 3D, pero en situaciones reales de juego (pista de tenis) no en un laboratorio de biomecánica (48, 49, 222). En cambio, del *estudio 4* se destaca la localización de una menor variabilidad motora en jugadores de mayor nivel de juego, lo cual ya había sido registrado con anterioridad (255), pero al igual que en el *estudio 3,* su fortaleza reside en que es uno de los primeros estudios que lo hacen en condiciones ecológicas. Los resultados anteriores abren una nueva frontera al análisis biomecánico ya que lo que antes suponía horas de preparativos (calibración de cámaras, colocación de marcadores epidérmicos, digitalización, procesado de datos, etc.), hoy en día podría realizarse incluso durante los partidos de competición sin que el jugador vea afectado su rendimiento (256).

La comparación cinemática y la variabilidad motora de los diferentes golpes de tenis no se han estudiado con frecuencia (la mayoría de los estudios han analizado la cinemática de los golpes de manera aislada), y resulta muy difícil encontrar estudios que permitan realizar una comparación entre los distintos golpes. En el *estudio 4*, los coeficientes de variación fueron mayores en los golpes de fondo que en los saques; esto puede deberse al hecho de que, en los golpes de derecha y revés, la pelota fue lanzada por una máquina de lanzamiento de pelotas, introduciendo más fuentes de variabilidad, como la trayectoria que sigue la pelota en el aire, el rebote de la pelota (determinado en parte por las características físicas de cada pelota) o el movimiento del jugador hacia la pelota. En el caso del saque, el jugador se encuentra en una situación más estática, la pelota es lanzada por el propio sujeto, no hay rebote de la pelota en el suelo y la trayectoria es más predecible, eliminando así posibles fuentes de variabilidad. En apoyo a esta hipótesis, Ilmane y LaRue sugieren que la complejidad de una tarea orientada a un objetivo depende de las diferencias en la restricción temporal de cada tarea (estos autores analizaron el lanzamiento de balonmano) (243). En términos sencillos, la variabilidad motora se ve afectada por las restricciones temporales. En general, es más complejo realizar un golpe de fondo donde el jugador no decide cuándo iniciar el movimiento que un golpe iniciado por el propio jugador, como un saque de tenis (243). En los golpes de fondo, el jugador tiene que ajustar la postura y los desplazamientos de los segmentos corporales en relación con la posición cambiante de la pelota, por lo que los sujetos modifican su comportamiento durante el lanzamiento en cada prueba. En el lanzamiento autoiniciado, el jugador determina el inicio del movimiento, reduciendo la complejidad del sistema humano-entorno (243).

La presente tesis doctoral tiene limitaciones y fortalezas que deben ser comentadas. En primer lugar, la fortaleza del *estudio 1* reside en sus fuertes implicaciones prácticas, ya que la confirmación de la validez y fiabilidad del reloj deportivo Polar Ignite® Precision Prime System midiendo frecuencia cardiaca durante entrenamiento de tenis, lo confirma como una útil herramienta portable (profesionales del fitness, entrenadores personales, fisiólogos y entrenadores) que permite controlar la respuesta fisiológica y planificar la temporada de los deportistas con mayor precisión. En cuanto a la limitación del *estudio 1,* a pesar de la eficacia comprobada del sistema de referencia utilizado (120–122), este no es el gold estándar de medición de frecuencia cardiaca.

Las limitaciones del *estudio 2* están asociadas con las interferencias electromagnéticas que provocan las estructuras metálicas del laboratorio sobre los IMUs (253), el tamaño muestral utilizado ya que no se determinó mediante métodos estadísticos y el sistema de sincronización entre ambos sistemas (IMU y OS) que no se realizó mediante impulso eléctrico o trigger. En cuanto a las fortalezas del *estudio 2,* tenemos que una vez demostrada la validez y fiabilidad de los sensores, suponen una herramienta de bajo coste y altas prestaciones en comparación con otros modelos existentes en el mercado.

El *estudio 3* tuvo las limitaciones habituales del uso de sensores inerciales que también se pueden aplicar a los *estudios 2 y 4*. Dichas limitaciones, son las posibles fuentes de error cuando se analizan movimientos humanos y que los instrumentos colocados en la piel pueden contener debido a sus movimientos. Además, en el *estudio 3* se asumió la limitación de solo incluir en la muestra a jugadores de tenis de nivel intermedio, lo que pudo provocar que las realizaciones técnicas de ambos tipos de revés no fuesen del todo perfectas en comparación con tenistas de nivel competición. Finalmente, en quinto lugar, el *estudio 4* debería haber medido la variabilidad motora en condiciones más controladas, eliminando fuentes de error como las distintas trayectorias de la pelota y los desplazamientos del jugador.

En líneas generales, las fortalezas de esta tesis residen en la utilización de tecnologías portables en situaciones reales de juego, lo cual aumenta significativamente las implicaciones prácticas de la misma. Debido a que permiten, tanto a profesionales clínicos como entrenadores, su aplicación con un menor coste económico y con mayor facilidad de configuración y uso. Al mismo tiempo que se reducen los tiempos, en que pueden proporcionar un feedback de calidad a sus deportistas, partiendo de datos monitorizados incluso durante los partidos de competición (256).

CONCLUSIONES GENERALES (Portada)

6. CONCLUSIONES GENERALES

6.1. CONCLUSIONES GENERALES EN ESPAÑOL

Los hallazgos de la presente tesis doctoral proporcionan nuevas evidencias en torno al tópico de las nuevas tecnologías portables aplicadas al tenis. Se validaron y aplicaron tecnologías portables en base a su bajo coste y posibilidades de aplicación en condiciones de campo (pista de tenis). La utilización de las tecnologías wearables en tenis supone un avance en la evaluación biomecánico/técnica y la prevención de lesiones musculo-esqueléticas. Además, las conclusiones del presente trabajo abren la puerta a la utilización de wearables incluso durante las competiciones, lo cual nos aportaría datos de relevancia a la hora de planificar la temporada de nuestros tenistas a entrenadores, preparadores físicos, médicos deportivos e investigadores de ciencias del deporte. De forma específica, se exponen los hallazgos y aportaciones de mayor importancia a continuación:

- El sistema fotoplestimográfico existente en los nuevos relojes deportivos de Polar® (Polar Precision Prime®) puede ser utilizado como medida válida y fiable de frecuencia cardiaca durante todas las partes de una sesión de entrenamiento de tenis (calentamiento, parte principal y vuelta a la calma) e intervalo de medición de 10 segundos. Confirmando que la precisión de este tipo de dispositivos no se ve alterada por los explosivos movimientos de tren superior del tenis. El Sistema PPP® podría permitir a jugadores y entrenadores ajustar y optimizar la intensidad de entrenamiento de acuerdo con sus objetivos y niveles de condición física. Además, al tener mediciones precisas en el calentamiento, la parte principal y la vuelta a la calma, los deportistas pueden obtener una visión más completa de su rendimiento cardiovascular a lo largo de toda la sesión de entrenamiento. Esto facilita la identificación de patrones y áreas de mejora. En definitiva, la herramienta PPP® permite a jugadores y entrenadores utilizar la información recopilada para ajustar estrategias de entrenamiento, evaluar la eficacia de diferentes enfoques y, en última instancia, trabajar hacia la mejora del rendimiento y la salud.

- NOTCH® como sistema de medida inercial es una herramienta válida y fiable para medir angulaciones de codo durante derecha de tenis para todas las frecuencias de muestreo analizadas (100 Hz, 200 Hz and 500 Hz). NOTCH® podría ser contemplado para su implementación en tiempo real durante sesiones de práctica o competiciones, permitiendo así una monitorización inmediata de las angulaciones de codo durante los golpes de tenis. Esto facilitaría la retroalimentación instantánea y la posibilidad de ajustar la técnica en tiempo real, además de prevenir posibles lesiones musculo-esqueléticas al tenista. A pesar de que los grados de acuerdo fueron aumentando conforme se incrementó la frecuencia de muestreo (los mejores resultados obtenidos fueron a 500 Hz), el sistema es versátil y puede adaptarse a diferentes configuraciones de grabación. Esto puede ser útil en entornos donde la frecuencia de muestreo puede variar debido a diferentes equipos o condiciones experimentales.
- El modelo de análisis biomecánico basado en el uso de sensores inerciales (giróscopos) es de utilidad para monitorizar la cinemática de los golpes de tenis durante experimentación de campo y puede ser fácilmente adaptado a otros deportes de raqueta. Además, se

confirmó que no existen diferencias entre el revés a una y dos manos en términos de velocidad y precisión para la muestra analizada. Aunque sí se encontraron diferencias significativas comparando la cinemática de ambos reveses. La capacidad del modelo biomecánico con sensores inerciales para analizar la cinemática de los golpes de tenis brinda a entrenadores y jugadores una herramienta valiosa para optimizar la técnica de los distintos golpeos. Al comprender las diferencias en la cinemática entre diferentes tipos de revés, se pueden identificar áreas específicas para mejorar, lo cual es aplicable al resto de golpes (derecha, saque, etc.).

- Se encontraron valores significativamente mayores de variabilidad motora para los golpes de fondo que durante el saque. Adicionalmente, los jugadores con mayor nivel de juego demostraron una menor variabilidad motora que los jugadores con menor experiencia. Por último, los tenistas con menor nivel de juego mostraron valores mayores de variabilidad motora en los sensores colocados en el antebrazo y la cabeza. La incorporación de datos sobre la variabilidad motora en los programas de entrenamiento de tenis, puede aportar a los entrenadores la oportunidad de diseñar sesiones de entrenamiento altamente específicas (según nivel de juego y experiencia), enfocadas en mejorar la estabilidad y consistencia de los golpes de tenis.
- En cuanto al asesor virtual de tenis y la aplicación Android se ha demostrado la posibilidad de introducción de este tipo de desarrollos para optimizar los procesos de enseñanza-aprendizaje de la técnica del tenis. Aunque, en el caso específico de nuestra aplicación, primero se le deberá introducir toda la información

recopilada en la presente tesis y posteriormente evaluar su eficacia objetiva en un futuro estudio de intervención. La introducción de este tipo tecnologías representa una innovación en la enseñanza deportiva. Esto puede atraer a nuevos practicantes, mantener el interés y proporcionar un enfoque moderno y atractivo para la instrucción de tenis. Finalmente, la extensa práctica (6) de deportes de raqueta de la población en la zona evaluada la habilitan para la futura introducción e implementación de la herramienta.

6.2. CONCLUSIONES GENERALES EN INGLÉS

The findings of this doctoral thesis provide new evidence on the topic of new wearable technologies applied to tennis. Portable technologies were validated and applied based on their low cost and application possibilities in field conditions (tennis court). The use of wearable technologies in tennis represents an advance in biomechanical/technical evaluation and the prevention of musculoskeletal injuries. Furthermore, the conclusions of this work open the door to the use of wearables even during competitions, which would provide us with relevant data when planning the season of our tennis players, coaches, physical trainers, sports doctors and health science researchers. sport. Specifically, the most important findings and contributions are presented below:

- The existing photoplethysmography system in the new Polar® sports watches (Polar Precision Prime®) can be used as a valid and reliable measure of heart rate during all parts of a tennis training session (warm-up, main part and return to the calm) and measurement interval of 10 seconds. Confirming that the precision of this type of device is not altered by the explosive upper body movements of tennis. The PPP® System allows players and coaches to adjust and optimize training intensity according to their goals and fitness levels. Additionally, by obtaining precise measurements during warm-up, the main training session, and cool down, athletes can gain a comprehensive overview of their cardiovascular performance throughout the entire training session. This facilitates the identification of patterns and areas for improvement. Ultimately, the PPP® tool empowers players and coaches to use the collected information to tailor training strategies, assess the effectiveness of different approaches, and, ultimately, work towards continuous improvement in performance and health.

- NOTCH® as an inertial measurement system is a valid and reliable tool to measure elbow angulations during tennis forehand for all the analysed sampling frequencies (100 Hz, 200 Hz and 500 Hz). NOTCH® could be considered for real-time implementation during practice sessions or competitions, enabling immediate monitoring of elbow angles during tennis strokes. This would facilitate instant feedback and the ability to adjust technique in real-time, in addition to preventing potential musculoskeletal injuries to the tennis player. Despite the fact that the degree of agreement increased as the sampling frequency was raised (with the best results obtained at 500 Hz), the system is versatile and can be adapted to different recording settings. This can be advantageous in environments where the sampling frequency may vary due to different equipment or experimental conditions.
- The biomechanical analysis model based on the use of inertial sensors (gyroscopes) is useful for monitoring the kinematics of tennis strokes during field experimentation and can be easily adapted to other racket sports. Furthermore, it was confirmed that there are no differences between the one-handed and two-handed backhand in terms of speed and precision for the sample analysed. Although significant differences were found in the kinematics between both tennis backhands. The capability of the biomechanical model with inertial sensors to analyse the kinematics of tennis strokes provides coaches and players with a valuable tool for optimizing the technique

of various strokes. By understanding the differences in kinematics among different types of backhands, specific areas for improvement can be identified, and this knowledge is applicable to other strokes (forehand, serve, etc.).

- Significantly higher values of motor variability were found for groundstrokes than during the serve. Additionally, players with a higher level of play demonstrated less motor variability than players with less experience. Finally, tennis players with a lower level of play showed higher values of motor variability in the sensors placed on the forearm and head. The integration of data on motor variability into tennis training programs can provide coaches with the opportunity to design highly specific training sessions (according to playing level and experience). This focus aims to improve the stability and consistency of tennis strokes.
- Regarding the virtual tennis avatar and the Android application, the possibility of introducing this type of development has been demonstrated to optimize the teaching-learning processes of tennis. Although, its objective effectiveness should be evaluated in a future intervention study. However, in the specific case of our application, it will be necessary to input all the information gathered in this thesis first, and subsequently, assess its effectiveness objectively in a future intervention study. The introduction of such technologies signifies an innovation in sports education. This can draw in new practitioners, maintain interest, and offer a modern and appealing approach to tennis instruction. Finally, the extensive practice of racket sports in the evaluated area (6) makes it well-suited for the future introduction and implementation of the tool.

6.3. LÍNEAS FUTURAS

Las líneas futuras de la presente tesis están enteramente relacionadas con la incorporación de nuevas funcionalidades a la aplicación Android® y a la utilización de la misma con fines de investigación. Las funcionalidades a implementar a la aplicación serán las siguientes:

- Integración de todos los indicadores de salud y rendimiento obtenidos con los estudios del presente trabajo.
- Introducción de más tipos de avatar a libre elección del usuario para que pueda encajar con sus preferencias: mujer, distintas edades y etnias.
- Implementación en la aplicación de cuestionarios pre y pos entrenamiento para registrar de forma objetiva el estado de motivación, fatiga, estrés, etc., del jugador.
- Integración de los distintos tipos de empuñaduras en función de la técnica deseada o idónea del tenista (continental, este de derecha, etc.).
- Desarrollo de la API de la aplicación para que sea capaz de recibir datos de sensores inerciales y sistemas con fotopletismografía, con el objetivo de que el asesor virtual de la aplicación pueda revelar alteraciones técnicas o detectar riesgos altos de lesión y prevenirlos.
- Incorporar biofeedback en función de los datos recibidos de los wearables.

Las mejoras anteriores buscan consolidar en un futuro la aplicación como una herramienta integral que abarque desde la simulación técnica hasta la monitorización a tiempo real del bienestar físico y emocional de los tenistas. Se realizará un estudio de intervención longitudinal basado en el uso de la aplicación, con el objetivo de evaluar cómo afecta al proceso de aprendizaje del tenis en una muestra de tenistas de distintos niveles de juego y edades. Además, la aplicación también puede ser de gran utilidad para clubes deportivos. Al abordar específicamente la etapa de iniciación al tenis, la aplicación se presenta como una herramienta valiosa para los clubes que buscan fomentar y desarrollar el interés de los jóvenes tenistas en sus primeras experiencias con este deporte. La adaptabilidad de la aplicación la convierten en un recurso versátil que puede complementar las actividades de formación ofrecidas por los clubes, facilitando la enseñanza y el aprendizaje en un contexto más amplio de desarrollo tenístico.

REFERENCIAS (Portada)

7. REFERENCIAS

1. Cádiz Gallardo MP, Pradas de la Fuente F, Moreno-Azze A, Carrasco Páez L. Physiological demands of racket sports: a systematic review. Front Psychol. 2023;14(March):1–9.
2. Kovacs MS. Tennis Physiology. Sport Med. 2007;37(3):189–98.
3. Martínez BS-A. Estudio de las características fisiológicas del tenis. ITF Coach Sport Sci Rev. 2014;(55):1–30.
4. Krizkova S, Tomaskova H, Tirkolaee EB. Sport performance analysis with a focus on racket sports: A review. Appl Sci. 2021;11(19).
5. Hoffmann D, Brixius K, Vogt T. Racket sports teaching implementations in physical education – A status quo analysis of German primary schools. J Phys Educ Sport. 2018;18(2):867–73.
6. Ruiz-Malagón EJ, Delgado-García G, López-Gutiérrez E, Zurita-Ortega F, Soto-Hermoso VM. Benefits of an intervention programme with racket sports in primary school students. Racket sports in elementary school students. Int J Racket Sport Sci. 2021;2(2):9–17.
7. Faber IR, Bustin PMJ, Oosterveld FGJ, Elferink-Gemser MT, Nijhuis-Van der Sanden MWG. Assessing personal talent determinants in young racquet sport players: a systematic review. J Sports Sci [Internet]. 2016;34(5):395–410. Available from: http://dx.doi.org/10.1080/02640414.2015.1061201
8. Guioti TDT, Toledo E de, Scaglia AJ. Esportes de raquete para deficientes intelectuais leves: uma proposta fundamentada na pedagogia do esporte. Rev Bras Educ Espec. 2014;20(3):357–70.
9. Cerezuela JL, Lirola MJ, Cangas AJ. Pickleball and mental health in adults: A systematic review. Front Psychol. 2023;14(February):1–9.
10. Oja P, Kelly P, Pedisic Z, Titze S, Bauman A, Foster C, et al. Associations of specific types of sports and exercise with all-cause and cardiovascular-disease mortality: a cohort study of 80 306 British adults. Br J Sports Med. 2017;51(10):812–7.
11. Jayanthi N, Esser S. Racket sports. Curr Sports Med Rep. 2013;12(5):329–36.
12. Pluim BM, Staal JB, Marks BL, Miller S, Miley D. Health benefits of tennis. Br J Sports Med. 2007;41(11):760–8.

13. Wörner EA, Safran MR. Racquet Sports: Tennis, Badminton, Racquetball, Squash. In: Piedade SR, Neyret P, Espregueira-Mendes J, Cohen M, Hutchinson MR, editors. Specific Sports-Related Injuries. Springer; 2021. p. 420–35.
14. RFET. Clasificación nacional RFET [Internet]. 2023 [cited 2023 Nov 15]. Available from: https://pgt.rfet.es/rfet/f?p=105:2::::RP,2:P2_SEXO_SEARCH:M&cs=1XF_n0PqkE2Y_sJY1bKHORpwL9ts
15. Pluim BM, Staal JB, Windler GE, Jayanthi N. Tennis injuries: Occurrence, aetiology, and prevention. Br J Sports Med. 2006;40(5):415–23.
16. Hutchinson MR, Laprade RF, Burnett Ii QM, Moss R, Terpstra J. Association National Boys' Tennis Championships from. Med Sci Sport Exerc. 1995;27(6):240.
17. Dines JS, Bedi A, Williams PN, Dodson CC, Ellenbecker TS, Altchek DW, et al. Tennis Injuries : Epidemiology ,. J Am Acad Orthop Surg. 2015;23(3):181–9.
18. Winge S, Jorgensen U, Lassen Nielsen A. Epidemiology of injuries in Danish championship tennis. Int J Sports Med. 1989;10(5):368–71.
19. Predoiu R. Intersegmental and Eye-hand Coordination in Elite Junior Tennis Players. Procedia - Soc Behav Sci [Internet]. 2015;187:107–12. Available from: http://dx.doi.org/10.1016/j.sbspro.2015.03.021
20. Elliott B. Biomechanics and tennis. Br J Sports Med. 2006;40(5):392–6.
21. Whiting WC, Zernicke RF. Biomechanics of Musculoskeletal Injury. Second. IL Human Kinetics; 2008.
22. Goislard de Monsabert B, Herbaut A, Cartier T, Vigouroux L. Electromyography-informed musculoskeletal modeling provides new insight into hand tendon forces during tennis forehand. Scand J Med Sci Sport. 2023;33(10):1958–75.
23. Knudson D, Elliott B. Biomechanics of Tennis Strokes. In: Biomedical Engineering Principles in Sports. Springer Science; 2004. p. 153–81.
24. Patel H, Lala S, Helfner B, Wong TT. Tennis overuse injuries in the upper extremity. Skeletal Radiol. 2021;50(4):629–44.
25. Marshall RN, Elliott BC. Long-axis rotation: The missing link in proximal-todistal segmental sequencing. J Sports Sci. 2000;18(4):247–54.

26. Genevois C, Reid M, Rogowski I, Crespo M. Performance factors related to the different tennis backhand groundstrokes: A review. Vol. 14, Journal of Sports Science and Medicine. 2014. p. 194–202.
27. Knudson D V. Intrasubject Variability of Upper Extremity Angular Kinematics in the Tennis Forehand Drive. Int J Sport Biomech. 2016;6(4):415–21.
28. O'Donoghue GP, Brown E. The Importance of Service in Grand Slam Singles Tennis. Int J Perform Anal Sport. 2017;8(3):70–8.
29. Abrams GD, Sheets AL, Andriacchi TP, Safran MR. Review of tennis serve motion analysis and the biomechanics of three serve types with implications for injury. Sport Biomech. 2011;10(4):378–90.
30. Ryu RK n., McCormick J, Jobe FW, Moynes DR, Antonelli DJ. An electromyographic analysis of shoulder function in tennis players. Am J Sports Med. 1988;16(5):481–5.
31. Abrams GD, Harris AHS, Andriacchi TP, Safran MR. Biomechanical analysis of three tennis serve types using a markerless system. Br J Sports Med. 2014;48(4):339–42.
32. Hornestam JF, Souza TR, Magalhães FA, Begon M, Santos TRT, Fonseca ST. The effects of knee flexion on tennis serve performance of intermediate level tennis players. Sensors. 2021;21(16):1–10.
33. Burkhart SS, Morgan CD, Ben Kibler W. The disabled throwing shoulder: Spectrum of pathology Part I: Pathoanatomy and biomechanics. Arthrosc - J Arthrosc Relat Surg. 2003;19(4):404–20.
34. Reid M, Elliott B, Crespo M. Mechanics and learning practices Associated with the Tennis forehand: A review. J Sport Sci Med. 2013;12(2):225–31.
35. Knudson D. Applying Biomechanics To The Qualitative Analysis Of The Forehand. XXIV ISBS Symp. 2006;(24 International Symposium on Biomechanics in Sports (2006)):1–5.
36. Kwon S, Pfister R, Hager RL, Hunter I, Seeley MK. Influence of tennis racquet kinematics on ball topspin angular velocity and accuracy during the forehand groundstroke. J Sport Sci Med. 2017;16(4):505–13.

37. Genevois C, Reid M, Creveaux T, Rogowski I. Kinematic differences in upper limb joints between flat and topspin forehand drives in competitive male tennis players. Sport Biomech. 2020;19(2):212–26.

38. Bahamonde RE, Knudson D. Kinetics of the upper extremity in the open and square stance tennis forehand. J Sci Med Sport. 2003;6(1):88–101.

39. Landlinger J, Lindinger S, Stöggl T, Wagner H, Müller E. Key factors and timing patterns in the tennis forehand of different skill levels. J Sport Sci Med. 2010;9(4):643–51.

40. Elliott B, Marsh T. A biomechanical comparison of the topspin and backspin forehand approach shots in tennis. J Sports Sci. 1989;7(3):215–27.

41. Delgado-García G, Vanrenterghem J, Muñoz-García A, Ruiz-Malagón EJ, Mañas-Bastidas A, Soto-Hermoso VM. Probabilistic structure of errors in forehand and backhand groundstrokes of advanced tennis players. Int J Perform Anal Sport. 2019;00(00):1–13.

42. Fernandez-Fernandez, Jaime; Kinner, Vanessa; Ferrauti A. The Physiological Demands of Hitting and Running in Tennis on Different Surfaces. J Strength y Cond Res. 2010;24(12):3255–64.

43. Reid M. Biomechanics of the one and two-handed backhands. ITF Coach Sport Sci Rev. 2001;

44. Stępień A, Bober T, Zawadzki J. The kinematics of trunk and upper extremities in one-handed and two-handed backhand stroke. J Hum Kinet. 2011;30(1):37–47.

45. Giangarra CE, Conroy B, Jobe FW, Pink M, Perry J. Electromyographic and cinematographic analysis of elbow function in tennis players using single- and double-handed backhand strokes. Am J Sports Med. 1993;21(3):394–9.

46. Blackwell JR, Cole KJ. Wrist kinematics differ in expert and novice tennis players performing the backhand stroke: Implications for tennis elbow. J Biomech. 1994;27(5):509–16.

47. Choppin S, Goodwill S, Haake S. Impact characteristics of the ball and racket during play at the Wimbledon qualifying tournament. Sport Eng. 2011;13(4):163–70.

48. Lo KC, Hsieh YC. Comparison of ball-and-racket impact force in two-handed backhand stroke stances for different-skill-level tennis players. J Sport Sci Med. 2016;15(2):301–7.

49. Knudson D, Blackwell J. Upper Extremity Angular Kinematics of the One-Handed Backhand Drive in Tennis Players With and Without Tennis Elbow. Int J Sports Med. 1997;13(4):79–82.
50. Busuttil NA, Reid M, Connolly M, Dascombe BJ, Middleton KJ. A kinematic analysis of the upper limb during the topspin double-handed backhand stroke in tennis. Sport Biomech [Internet]. 2022;21(9):1046–64. Available from: https://doi.org/10.1080/14763141.2020.1726994
51. Cooke K, Davey PR, Cooke K, Davey PR. Tennis ball diameter : the effect on performance and the concurrent physiological responses Tennis ball diameter : the effect on performance and the concurrent physiological responses. J Sports Sci. 2011;23:31–9.
52. Fernandez-Fernandez J, Sanz-Rivas D, Mendez-Villanueva A. A review of the activity profile and physiological demands of tennis match play. Vol. 31, Strength and Conditioning Journal. 2009. p. 15–26.
53. The A. physiological demands surfaces. J Strength Cond Res. 2010;24(12):3255–64.
54. Hornery DJ, Farrow D, Mujika I, Young W. An integrated physiological and performance profile of professional tennis. Br J Sports Med. 2007;41(8):531–6.
55. Pluim BM, Jansen MGT, Williamson S, Berry C, Camporesi S, Fagher K, et al. Physical Demands of Tennis Across the Different Court Surfaces, Performance Levels and Sexes: A Systematic Review with Meta-analysis [Internet]. Vol. 53, Sports Medicine. Springer International Publishing; 2023. p. 807–36. Available from: https://doi.org/10.1007/s40279-022-01807-8
56. Smekal G, Von Duvillard SP, Rihacek C, Pokan R, Hofmann P, Baron R, et al. A physiological profile of tennis match play. Med Sci Sports Exerc. 2001;33(6):999–1005.
57. Docherty D. Physical Education, University. Br J Sports Med. 1982;16(2):96–100.
58. Mavvidis A, Koronas K, Pantelidis D, Vamvakoudis S. The effects of heart rate on tennis serve velocity. J Hum Mov Stud. 2007;52(2):81–93.
59. Barfield JP, Coleman TA, Malone LA. Comparison of heart rate response to tennis activity between persons with and without spinal cord injuries: Implications for a training threshold. Res Q Exerc Sport. 2009;80(1):71–7.

60. García-Gonzálvez S, López-Plaza D, Abellán-Aynés O. Influence of Competition on Anxiety and Heart Rate Variability in Young Tennis Players. Healthc. 2022;10(11):1–9.
61. Reid M, Crespo M, Lay B, Berry J. Skill acquisition in tennis: Research and current practice. Vol. 10, Journal of Science and Medicine in Sport. 2007. p. 1–10.
62. Gül M, Çelik D. The Effect of Eight-Weeks Coordinatıon Training on Tennis and Motor Skills Performance on 8-10 Years Children. Pakistan J Med Heal Sci. 2021;15(6):1578–82.
63. Crespo M, Miley D. ITF advanced coaches manual. 3rd ed. London: ITF; 2007.
64. Williams AM, Ward P, Knowles JM, Smeeton NJ. Anticipation skill in a real-world task: Measurement, training, and transfer in tennis. J Exp Psychol Appl. 2002;8(4):259–70.
65. Cervelló E, Rosa FJS, Calvo TG, Jiménez R, Iglesias D. Young tennis players' competitive task involvement and performance: The role of goal orientations, contextual motivational climate, and coach-initiated motivational climate. J Appl Sport Psychol. 2007;19(3):304–21.
66. Rana M, Mittal V. Wearable Sensors for Real-Time Kinematics Analysis in Sports: A Review. IEEE Sens J. 2021;21(2):1187–207.
67. Delgado-García G, Vanrenterghem J, Ruiz-Malagón EJ, Molina-García P, Courel-Ibáñez J, Soto-Hermoso VM. IMU gyroscopes are a valid alternative to 3D optical motion capture system for angular kinematics analysis in tennis. Proc Inst Mech Eng Part P J Sport Eng Technol. 2021;235(1):3–12.
68. Bilić Z, Dukarić V, Šanjug S, Barbaros P, Knjaz D. The Concurrent Validity of Mobile Application for Tracking Tennis Performance. Appl Sci. 2023;13(10).
69. Pineda-Hernández S. How to play under pressure: EEG monitoring of mental activation training in a professional tennis player. Physiol Behav. 2022;250(November 2021).
70. Marutani Y, Konda S, Ogasawara I, Yamasaki K, Yokoyama T, Maeshima E, et al. Gaussian mixture modeling of acceleration-derived signal for monitoring external physical load of tennis player. Front Physiol. 2023;14(March):1–8.

71. Grimpampi E, Masci I, Pesce C, Vannozzi G. Quantitative assessment of developmental levels in overarm throwing using wearable inertial sensing technology. J Sports Sci [Internet]. 2016;34(18):1759–65. Available from: http://dx.doi.org/10.1080/02640414.2015.1137341

72. Hernández-Davó JL, Moreno FJ, Sanz-Rivas D, Hernández-Davó H, Coves Á, Caballero C. Variations in kinematic variables and performance in the tennis serve according to age and skill level. Int J Perform Anal Sport [Internet]. 2019;19(5):749–62. Available from: https://doi.org/10.1080/24748668.2019.1653036

73. Fitzpatrick A, Stone JA, Choppin S, Kelley J. A simple new method for identifying performance characteristics associated with success in elite tennis. Int J Sport Sci Coach. 2019;14(1):43–50.

74. Gallo-Salazar C, Del Coso J, Sanz-Rivas D, Fernandez-Fernandez J. Game activity and physiological responses of young tennis players in a competition with 2 consecutive matches in a day. Int J Sports Physiol Perform. 2019;14(7):887–93.

75. Kekelekis A, Nikolaidis PT, Moore IS, Rosemann T, Knechtle B. Risk factors for upper limb injury in tennis players: A systematic review. Int J Environ Res Public Health. 2020;17(8).

76. Giménez-egido JM, Ortega E, Verdu-conesa I, Cejudo A, Torres-luque G. Using smart sensors to monitor physical activity and technical–tactical actions in junior tennis players. Int J Environ Res Public Health. 2020;17(3):12–5.

77. Edelmann-Nusser A, Raschke A, Bentz A, Montenbruck S, Edelmann-Nusser J, Lames M. Validation of Sensor-Based Game Analysis Tools in Tennis. Int J Comput Sci Sport. 2019;18(2):49–59.

78. Topley M, Richards JG. A comparison of currently available optoelectronic motion capture systems. J Biomech [Internet]. 2020;106:109820. Available from: https://doi.org/10.1016/j.jbiomech.2020.109820

79. Robert-Lachaine X, Mecheri H, Larue C, Plamondon A. Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis. Med Biol Eng Comput. 2017;55(4):609–19.

80. Camomilla V, Bergamini E, Fantozzi S, Vannozzi G. Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: A systematic review. Sensors (Switzerland). 2018;18(3).

81. Hadžić V, Germič A, Filipčič A. Validity and reliability of a novel monitoring sensor for the quantification of the hitting load in tennis. PLoS One. 2021;16(7 July):1–13.

82. Teufl W, Miezal M, Taetz B, Frohlichi M, Bleser G. Validity of inertial sensor based 3D joint kinematics of static and dynamic sport and physiotherapy specific movements. PLoS One. 2019;14(2):1–18.

83. Pedro B, Cabral S, Veloso AP. Concurrent validity of an inertial measurement system in tennis forehand drive. J Biomech [Internet]. 2021;121:110410. Available from: https://doi.org/10.1016/j.jbiomech.2021.110410

84. Reid M, Giblin G, Whiteside D. A kinematic comparison of the overhand throw and tennis serve in tennis players: How similar are they really? J Sports Sci [Internet]. 2015;33(7):713–23. Available from: http://dx.doi.org/10.1080/02640414.2014.962572

85. Padulo J, Chamari K, Ardigò LP. Walking and running on treadmill: The standard criteria for kinematics studies. Muscles Ligaments Tendons J. 2014;4(2):159–62.

86. Ju YY, Chu WT, Shieh WY, Cheng HYK. Sensors for wheelchair tennis: Measuring trunk and shoulder biomechanics and upper extremity vibration during backhand stroke. Sensors. 2021;21(19).

87. Yam JW, Pan JW, Kong PW. Measuring upper limb kinematics of forehand and backhand topspin drives with imu sensors in wheelchair and able-bodied table tennis players. Sensors. 2021;21(24).

88. Fallahtafti F, Wurdeman SR, Yentes JM. Sampling rate influences the regularity analysis of temporal domain measures of walking more than spatial domain measures. Gait Posture [Internet]. 2021;88(January):216–20. Available from: https://doi.org/10.1016/j.gaitpost.2021.05.031

89. Gómez-Carmona CD, Rojas-Valverde D, Rico-González M, Ibáñez SJ, Pino-Ortega J. What is the most suitable sampling frequency to register accelerometry-based workload? A case study in soccer. Proc Inst Mech Eng Part P J Sport Eng Technol. 2021;235(2):114–21.
90. Chow JW, Carlton LG, Lim YT, Chae WS, Shim JH, Kuenster AF, et al. Comparing the pre- and post-impact ball and racquet kinematics of elite tennis players' first and second serves: A preliminary study. J Sports Sci. 2003;21(7):529–37.
91. Kibler W Ben, Van der Meer D. Chapter Six: Mastering the Kinetic Chain [Internet]. Human Kine. Champaign, IL: Human Kinetics; 2001. 98–113 p. Available from: http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=27976198&site=ehost-live
92. Hermand E, Cassirame J, Ennequin G, Hue O. Validation of a Photoplethysmographic Heart Rate Monitor: Polar OH1. Int J Sports Med. 2019;40(7):462–7.
93. Alian AA, Shelley KH. Photoplethysmography. Best Pract Res Clin Anaesthesiol. 2014;28(4):395–406.
94. Falter M, Budts W, Goetschalckx K, Cornelissen V, Buys R. Accuracy of apple watch measurements for heart rate and energy expenditure in patients with cardiovascular disease: Cross-sectional study. JMIR mHealth uHealth. 2019;7(3):1–9.
95. Schneider C, Hanakam F, Wiewelhove T, Döweling A, Kellmann M, Meyer T, et al. Heart rate monitoring in team sports-A conceptual framework for contextualizing heart rate measures for training and recovery prescription. Front Physiol. 2018;9(MAY):1–19.
96. Lang M. Beyond Fitbit: A Critical Appraisal of Optical Heart Rate Monitoring Wearables and Apps, Their Current Limitations and Legal Implications. Alb L J Sci Tech. 2017;39(March):39.
97. Katz L, Parker J, Tyreman H, Kopp G, Levy RM, Chang E. Virtual reality in sport and wellness: Promise and reality. Int J Comput Sci Sport [Internet]. 2006;4(1):4–16. Available from: http://www.citeulike.org/group/532/article/775527
98. Novatchkov H, Baca A. Artificial intelligence in sports on the example of weight training. J Sport Sci Med. 2013;12(1):27–37.

99. Neumann DL, Moffitt RL, Thomas PR, Loveday K, Watling DP, Lombard CL, et al. A systematic review of the application of interactive virtual reality to sport. Virtual Real. 2018;22(3):183–98.
100. Baca A, Dabnichki P, Heller M, Kornfeind P. Ubiquitous computing in sports: A review and analysis. J Sports Sci. 2009;27(12):1335–46.
101. Appelbaum LG, Erickson G. Sports vision training: A review of the state-of-the-art in digital training techniques. Int Rev Sport Exerc Psychol [Internet]. 2018;11(1):160–89. Available from: http://dx.doi.org/10.1080/1750984X.2016.1266376
102. Bideau B, Kulpa R, Vignais N, Brault S, Multon F, Craig C. Using virtual reality to analyze sports performance. IEEE Comput Graph Appl. 2010;30(2):14–21.
103. "BotBoxer / Interactive Boxing Machines / VR/AR Punching Bag Arcade Games." [Internet]. 2020. [cited 2020 Apr 25]. Available from: https://botboxer.com/ (accessed Apr. 25, 2020)
104. Zhang L, Brunnett G, Petri K, Danneberg M, Masik S, Bandow N, et al. KaraKter: An autonomously interacting Karate Kumite character for VR-based training and research. Comput Graph [Internet]. 2018;72:59–69. Available from: https://doi.org/10.1016/j.cag.2018.01.008
105. ITF. World Tennis Number [Internet]. 2023 [cited 2023 Nov 15]. Available from: https://worldtennisnumber.com/eng/your-number
106. International Tennis Federation. ITF Approved Tennis Balls and Classified Court Surfaces - a guide to products and test methods. 2015; Available from: https://www.itftennis.com/media/2714/2020-itf-approved-tennis-balls-classified-court-surfaces-and-recognised-courts.pdf
107. Lyons M, Al-Nakeeb Y, Hankey J, Nevill A. The effect of moderate and high-intensity fatigue on groundstroke accuracy in expert and non-expert tennis players. J Sport Sci Med. 2013;12(2):298–308.

108. Vilas-Boas M do C, Choupina HMP, Rocha AP, Fernandes JM, Cunha JPS. Full-body motion assessment: Concurrent validation of two body tracking depth sensors versus a gold standard system during gait. J Biomech [Internet]. 2019;87:189–96. Available from: https://doi.org/10.1016/j.jbiomech.2019.03.008
109. Umek A, Kos A. Validation of UWB positioning systems for player tracking in tennis. Pers Ubiquitous Comput. 2022;26(4):1023–33.
110. Tan KK, Huang S, Liang W, Mamun A Al, Member S. Validation of Player and Ball Tracking with a Local Positioning System. Sensors. 2021;59(9):3501–9.
111. Nagymátê G, M. Kiss R. Application of OptiTrack motion capture systems in human movement analysis. Recent Innov Mechatronics. 2018;5(1.):1–9.
112. Zaiontz C. Real Statistic Using Excel tool [Internet]. 2018. Available from: https://www.real-statistics.com/
113. Vanrenterghem J. Biomechanics Toolbar [Internet]. 2016. Available from: http://www.biomechanicstoolbar.org/
114. Lenhard, W. & Lenhard A. Psychometric freeware [Internet]. Calculation of Effect Sizes. 2016 [cited 2023 Nov 17]. Available from: https://www.psychometrica.de/effect_size.html
115. Kyriacou PA. Pulse oximetry in the oesophagus. Physiol Meas. 2006;27(1).
116. Allen J. Photoplethysmography and its application in clinical physiological measurement. Physiol Meas. 2007;28(3).
117. Kyriacou PA, Chatterjee S. The origin of photoplethysmography. In: Photoplethysmography. Academic Press; 2022. p. 17–43.
118. Zhang Z. Heart rate monitoring from wrist-type photoplethysmographic (PPG) signals during intensive physical exercise. 2014 IEEE Glob Conf Signal Inf Process Glob 2014. 2014;698–702.
119. Collins T, Woolley SI, Oniani S, Pires IM, Garcia NM, Ledger SJ, et al. Version reporting and assessment approaches for new and updated activity and heart rate monitors. Sensors (Switzerland). 2019;19(7):1–13.

120. Gilgen-Ammann R, Schweizer T, Wyss T. RR interval signal quality of a heart rate monitor and an ECG Holter at rest and during exercise. Eur J Appl Physiol [Internet]. 2019;119(7):1525–32. Available from: https://doi.org/10.1007/s00421-019-04142-5
121. Boudreaux BD, Hebert EP, Hollander DB, Williams BM, Cormier CL, Naquin MR, et al. Validity of Wearable Activity Monitors during Cycling and Resistance Exercise. Vol. 50, Medicine and Science in Sports and Exercise. 2018. 624–633 p.
122. Caminal P, Sola F, Gomis P, Guasch E, Perera A, Soriano N, et al. Validity of the Polar V800 monitor for measuring heart rate variability in mountain running route conditions. Eur J Appl Physiol [Internet]. 2018;118(3):669–77. Available from: http://dx.doi.org/10.1007/s00421-018-3808-0
123. Nystrom M. How optical heart rate monitoring works with Polar Precision Prime. 2019.
124. Boloursaz Mashhadi M, Asadi E, Eskandari M, Kiani S, Marvasti F. Heart Rate Tracking using Wrist-Type Photoplethysmographic (PPG) Signals during Physical Exercise with Simultaneous Accelerometry. IEEE Signal Process Lett. 2015;23(2):227–31.
125. Ruiz-Malagón EJ, Ruiz-Alias SA, García-Pinillos F, Delgado-García G, Soto-Hermoso VM. Comparison between photoplethysmographic heart rate monitor from Polar Vantage M and Polar V800 with H10 chest strap while running on a treadmill: Validation of the Polar Precision PrimeTM photoplestimographic system. Proc Inst Mech Eng Part P J Sport Eng Technol. 2021;235(3):212–8.
126. Ruiz-alias SA, García-Pinillos F, Soto-Hermoso VM, Ruiz-malagon EJ. Heart rate monitoring of the endurance runner during high intensity interval training : Influence of device used on training functions. Proc Inst Mech Eng Part P J Sport Eng Technol. 2021;237(3):166–72.

127. Budig M, Keiner M, Stoohs R, Hoffmeister M, Höltke V. Heart rate and distance measurement of two multisport activity trackers and a cellphone app in different sports: A cross-sectional validation and comparison field study. Sensors. 2022;22(1).

128. Muggeridge DJ, Hickson K, Davies AV, Giggins OM, Megson IL, Gorely T, et al. Measurement of heart rate using the polar OH1 and fitbit charge 3 wearable devices in healthy adults during light, moderate, vigorous, and sprint-based exercise: Validation study. JMIR mHealth uHealth. 2021;9(3).

129. Nuuttila OP, Korhonen E, Laukkanen J, Kyröläinen H. Validity of the wrist-worn polar vantage v2 to measure heart rate and heart rate variability at rest. Sensors. 2022;22(1).

130. Ling CHY, de Craen AJM, Slagboom PE, Gunn DA, Stokkel MPM, Westendorp RGJ, et al. Accuracy of direct segmental multi-frequency bioimpedance analysis in the assessment of total body and segmental body composition in middle-aged adult population. Clin Nutr [Internet]. 2011;30(5):610–5. Available from: http://dx.doi.org/10.1016/j.clnu.2011.04.001

131. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41(1):3–12.

132. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. J Chiropr Med. 2016;15(2):155–63.

133. Fokkema T, Kooiman TJ, Krijnen WP, Van der Schans CP, De Groot M. Reliability and validity of ten consumer activity trackers depend on walking speed. Med Sci Sport Exerc. 2017;49(4):793–800.

134. Bland MJ, Altman G. Comparing methods of measurement : why plotting difference against standard method is misleading. Lancet. 1995;346:1085–7.

135. Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sport Med. 1998;26:217–38.

136. Tedesco S, Sica M, Ancillao A, Timmons S, Barton J, O'Flynn B. Accuracy of consumer-level and research-grade activity trackers in ambulatory settings in older adults. PLoS One. 2019;14(5):1–17.

137. Goodie JL, Larkin KT, Schauss S. Validation of Polar heart rate monitor for assessing heart rate during physical and mental stress. J Psychophysiol. 2000;14(3):159–64.
138. Jagim AR, Koch-Gallup N, Camic CL, Kroening L, Nolte C, Schroeder C, et al. The accuracy of fitness watches for the measurement of heart rate and energy expenditure during moderate intensity exercise. J Sports Med Phys Fitness. 2021;61(2):205–11.
139. Henriksen A, Svartdal F, Grimsgaard S, Hartvigsen G, Hopstock LA. Polar Vantage and Oura Physical Activity and Sleep Trackers: Validation and Comparison Study. JMIR Form Res. 2022;6(5).
140. Hettiarachchi IT, Hanoun S, Nahavandi D, Nahavandi S. Validation of Polar OH1 optical heart rate sensor for moderate and high intensity physical activities. PLoS One. 2019;14(5).
141. Hernando D, Garatachea N, Almeida R, Casajus JA, Bailón R. Validation of heart rate monitor Polar RS800 for heart rate variability analysis during exercise. J Strength Cond Res. 2018;32(3):716–25.
142. Schubert M, Clark A, De La Rosa A. The Polar® OH1 Optical Heart Rate Sensor is Valid during Moderate-Vigorous Exercise. Sport Med Int Open. 2018;02(03):E67–70.
143. Lamberts RP, Lemmink KA, Durandt JJ, Lambert MI. Variation in heart rate during submaximal exercise: implications for monitoring training. J strength Cond Res. 2004;18(3):641–5.
144. Gillinov S, Etiwy M, Wang R, Blackburn G, Phelan D, Gillinov AM, et al. Variable accuracy of wearable heart rate monitors during aerobic exercise. Med Sci Sports Exerc. 2017;49(8):1697–703.
145. Ahmad N, Ghazilla RAR, Khairi NM, Kasi V. Reviews on Various Inertial Measurement Unit (IMU) Sensor Applications. Int J Signal Process Syst. 2013;1(2):256–62.
146. Buthe L, Blanke U, Capkevics H, Troster G. A wearable sensing system for timing analysis in tennis. BSN 2016 - 13th Annu Body Sens Networks Conf. 2016;43–8.
147. Ganser A, Hollaus B, Stabinger S. Classification of tennis shots with a neural network approach. Sensors. 2021;21(17):1–20.

148. de Vries WHK, Veeger HEJ, Baten CTM, van der Helm FCT. Magnetic distortion in motion labs, implications for validating inertial magnetic sensors. Gait Posture. 2009;29(4):535–41.

149. Roetenberg D, Luinge H, Slycke P. Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors. Xsens Motion Technol BV, … [Internet]. 2009;1–7. Available from: http://www.xsens.com/images/stories/PDF/MVN_white_paper.pdf

150. Pedro B, João F, Lara JPR, Cabral S, Carvalho J, Veloso AP. Evaluation of Upper Limb Joint Contribution to Racket Head Speed in Elite Tennis Players Using IMU Sensors: Comparison between the Cross-Court and Inside-Out Attacking Forehand Drive. Sensors. 2022;22(3).

151. Ishikawa T, Murakami T. An approach to 3D gyro sensor based motion analysis in tennis forehand stroke. IECON 2015 - 41st Annu Conf IEEE Ind Electron Soc. 2015;2354–9.

152. Zhao H, Wang S, Zhou G, Jung W. Tenniseye: Tennis ball speed estimation using a racket-mounted motion sensor. IPSN 2019 - Proc 2019 Inf Process Sens Networks. 2019;241–52.

153. Landlinger J, Lindinger SJ, Stöggl T, Wagner H, MüLler E. Kinematic differences of elite and high-performance tennis players in the cross court and down the line forehand. Sport Biomech. 2010;9(4):280–95.

154. Whiteside D, Elliott BC, Lay B, Reid M. Coordination and variability in the elite female tennis serve. J Sports Sci. 2015;33(7):675–86.

155. Bellusci G, Roetenberg D, Dijkstra F, Luinge H, Slycke P. Xsens MVN MotionGrid : Drift-free human motion tracking using tightly coupled ultra-wideband and miniature inertial sensors. Xsens Technol White Pap. 2011;1–10.

156. Gao Y, Tebbe J, Krismer J, Zell A. Markerless Racket Pose Detection and Stroke Classification Based on Stereo Vision for Table Tennis Robots. Proc - 3rd IEEE Int Conf Robot Comput IRC 2019. 2019;189–96.

157. Kriz P, Riha K, Dutta MK. Automatic determination of the position of a tennis player using a pair of cameras. 2017 40th Int Conf Telecommun Signal Process TSP 2017. 2017;2017-Janua(mm):763–8.

158. Kumar A, Chavan PS, Sharatchandra VK, David S, Kelly P, O'Connor NE. 3D Estimation and visualization of motion in a multicamera network for sports. Proc - 2011 Irish Mach Vis Image Process Conf IMVIP 2011. 2011;15–9.

159. Blair S, Duthie G, Robertson S, Hopkins W, Ball K. Concurrent validation of an inertial measurement system to quantify kicking biomechanics in four football codes. J Biomech [Internet]. 2018;73:24–32. Available from: https://doi.org/10.1016/j.jbiomech.2018.03.031

160. Fantozzi S, Giovanardi A, Magalhães FA, Di Michele R, Cortesi M, Gatta G. Assessment of three-dimensional joint kinematics of the upper limb during simulated swimming using wearable inertial-magnetic measurement units. J Sports Sci [Internet]. 2016;34(11):1073–80. Available from: http://dx.doi.org/10.1080/02640414.2015.1088659

161. Bouvier B, Duprey S, Claudon L, Dumas R, Savescu A. Upper limb kinematics using inertial and magnetic sensors: Comparison of sensor-to-segment calibrations. Sensors (Switzerland). 2015;15(8):18813–33.

162. Harnett K, Plint B, Chan KY, Clark B, Netto K, Davey P, et al. Validating an inertial measurement unit for cricket fast bowling: a first step in assessing the feasibility of diagnosing back injury risk in cricket fast bowlers during a tele-sport-and-exercise medicine consultation. PeerJ. 2022;10.

163. Goreham JA, MacLean KFE, Ladouceur M. The validation of a low-cost inertial measurement unit system to quantify simple and complex upper-limb joint angles. J Biomech [Internet]. 2022;134(February):111000. Available from: https://doi.org/10.1016/j.jbiomech.2022.111000

164. Seeley MK, Funk MD, Denning WM, Hager RL. Tennis forehand kinematics change as post-impact ball speed is altered. In: The Biomechanics of Batting, Swinging, and Hitting. Routledge; 2016. p. 181–92.

165. Landlinger J, Stöggl T, Lindinger S, Wagner H, Müller E. Differences in ball speed and accuracy of tennis groundstrokes between elite and high-performance players. Eur J Sport Sci. 2012;12(4):301–8.

166. Wu SK, Gross MT, Prentice WE, Yu B. Comparison of ball-and-racquet impact force between two tennis backhand stroke techniques. J Orthop Sports Phys Ther. 2001;31(5):247–54.

167. Keaney EM, Reid M. Quantifying hitting activity in tennis with racket sensors: new dawn or false dawn? Sport Biomech [Internet]. 2020;19(6):831–9. Available from: https://doi.org/10.1080/14763141.2018.1535619

168. Zhang S, Murray P, Zillmer R, Eston RG, Catt M, Rowlands A V. Activity classification using the genea: Optimum sampling frequency and number of axes. Med Sci Sports Exerc. 2012;44(11):2228–34.

169. Lloyd DG, Alderson J, Elliott BC. An upper limb kinematic model for the examination of cricket bowling: A case study of Mutiah Muralitharan. J Sports Sci. 2000;18(12):975–82.

170. Winter D. Biomechanics and motor control of human movement. John wiley & sons; 2009.

171. Wundersitz DWT, Netto KJ, Aisbett B, Gastin PB. Validity of an upper-body-mounted accelerometer to measure peak vertical and resultant force during running and change-of-direction tasks. Sport Biomech. 2013;12(4):403–12.

172. Edwards WB, Derrick TR, Hamill J. Time series analysis in biomechanics. In: Handbook of Human Motion. Springer International Publishing; 2017. p. 1–24.

173. Li L, Caldwell GE. Coefficient of cross correlation and the time domain correspondence. J Electromyogr Kinesiol. 1999;9(6):385–9.

174. Lawrence I, Lin K. A Concordance Correlation Coefficient to Evaluate Reproducibility Author (s): Lawrence I-Kuei Lin Published by : International Biometric Society Stable URL : http://www.jstor.org/stable/2532051 REFERENCES Linked references are available on JSTOR for thi. Biomatrics. 1989;45(1):255–68.

175. Lin L, Hedayat AS, Sinha B, Yang M. Statistical methods in assessing agreement: Models, issues, and tools. J Am Stat Assoc. 2002;97(457):257–70.

176. McGinley JL, Baker R, Wolfe R, Morris ME. The reliability of three-dimensional kinematic gait measurements: A systematic review. Gait Posture. 2009;29(3):360–9.

177. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, NJ: Erlbaum; 1988.

178. Barreto J, Peixoto C, Cabral S, Williams AM, Casanova F, Pedro B, et al. Concurrent validation of 3d joint angles during gymnastics techniques using inertial measurement units. Electronics. 2021;10(11):1–16.

179. Whiteside D, Elliott B, Lay B, Reid M. The effect of age on discrete kinematics of the elite female tennis serve. J Appl Biomech. 2013;29(5):573–82.

180. Tubez F, Schwartz C, Paulus J, Croisier JL, Brüls O, Denoël V, et al. Which tool for a tennis serve evaluation? A review. Int J Perform Anal Sport [Internet]. 2017;17(6):1007–33. Available from: http://doi.org/10.1080/24748668.2017.1419407

181. Boyd LJ, Ball K, Aughey RJ. The reliability of minimaxx accelerometers for measuring physical activity in australian football. Int J Sports Physiol Perform. 2011;6(3):311–21.

182. Wundersitz DWT, Gastin PB, Robertson S, Davey PC, Netto KJ. Validation of a Trunk-mounted Accelerometer to Measure Peak Impacts during Team Sport Movements. Int J Sports Med. 2015;36(9):742–6.

183. Sharma M, Srivastava R, Anand A, Prakash D, Kaligounder L. Wearable motion sensor based phasic analysis of tennis serve for performance feedback. IEEE Int Conf Acoust Speech, Signal Process 2017. 2017;5945–9.

184. Kos M, Ženko J, Vlaj D, Kramberger I. Tennis stroke detection and classification using miniature wearable IMU device. Int Conf Syst Signals, Image Process. 2016;2016-June:7–10.

185. Ohshima S, Kato S, Sakuma T. Correlation Analysis between Tennis Swing Features and Tennis Skillfulness Using Six-Axis Sensor. 2020 IEEE 9th Glob Conf Consum Electron GCCE 2020. 2020;950–1.

186. Pei W, Wang J, Xu X, Wu Z, Du X. An embedded 6-axis sensor based recognition for tennis stroke. 2017 IEEE Int Conf Consum Electron ICCE 2017. 2017;55–8.

187. Roetert EP, Garret GE, Brown SW, Camaione DN. Performance profiles of nationally ranked junior tennis players. J Strength Cond Res. 1992;6(4):225–31.
188. Delgado-García G, Vanrenterghem J, Muñoz-García A, Ruiz-Malagón EJ, Mañas-Bastidas A, Soto-Hermoso VM. Probabilistic structure of errors in forehand and backhand groundstrokes of advanced tennis players. Int J Perform Anal Sport [Internet]. 2019;19(5):698–710. Available from: https://doi.org/10.1080/24748668.2019.1647733
189. Fernández-Fenández J, Kinner V, Ferrauti A. The physiological demands of hitting and running in tennis on different surfaces. J Strength Cond Res. 2010;24(12):3255–64.
190. Reid M. Biomechanics of the one and two-handed backhands. ITF Coach Sport Sci Rev. 2001;9(24):8–12.
191. Roetert EP, Brody H, Dillman CJ, Groppel JL, Schultheis JM. The biomechanics of tennis elbow. Clin Sports Med. 1995;14(1):47–57.
192. Bahamonte R. Review of the biomechanical function of the elbow joint during tennis strokes. Int Sport J. 2005;6(2):42–63.
193. Reid M, Elliot B. Tennis: The one-and two-handed backhands in tennis. Sport Biomech. 2002;1(1):47–68.
194. Akutagawa S, Kojima T. Trunk rotation torques through the hip joints during the one- and two-handed backhand tennis strokes. J Sports Sci. 2005;23(8):781–93.
195. Allen T, Choppin S, Knudson D. A review of tennis racket performance parameters. Sport Eng [Internet]. 2016;19(1):1–11. Available from: http://dx.doi.org/10.1007/s12283-014-0167-x
196. Cosac G, Ionescu DB. Research approach for outlining the biomechanical parameters of the tennis serve. Palestrica Third Millenn Civiliz Sport [Internet]. 2015;16(4):333–7. Available from: https://go.openathens.net/redirector/leedsmet.ac.uk?url=http%3A%2F%2Fsearch.ebscohost.com%2Flogin.aspx%3Fdirect%3Dtrue%26db%3Da9h%26AN%3D114631675%26site%3Deds-live%26scope%3Dsite
197. Bertolotti GM, Cristiani AM, Colagiorgio P, Romano F, Bassani E, Caramia N, et al. A Wearable and Modular Inertial Unit for Measuring Limb Movements and Balance Control Abilities. IEEE Sens J. 2015;16(3):790–7.

198. Ahmadi A, Rowlands DD, James DA. Development of inertial and novel marker-based techniques and analysis for upper arm rotational velocity measurements in tennis. Sport Eng. 2010;12(4):179–88.

199. Hansen C, Martin C, Rezzoug N, Gorce P, Bideau B, Isableu B. Sequence-dependent rotation axis changes in tennis. Sport Biomech [Internet]. 2017;16(3):411–23. Available from: http://doi.org/10.1080/14763141.2017.1332237

200. Buthe L, Blanke U, Capkevics H, Troster G. A wearable sensing system for timing analysis in tennis. In: BSN 2016 - 13th Annual Body Sensor Networks Conference. 2016. p. 43–8.

201. Brody H, Roetert P. Optimizing ball and racket interaction. In: In Biomedical Engineering Principles in Sports. Boston, MA: Springer; 2004. p. 183–206.

202. Bourke AK, Lyons GM. A threshold-based fall-detection algorithm using a bi-axial gyroscope sensor. Med Eng Phys. 2008;30(1):84–90.

203. Van Den Tillaar R, Ettema G. A comparison between novices and experts of the velocity-accuracy trade-off in overarm throwing. Percept Mot Skills. 2006;103(2):503–14.

204. Kelley J, Choppin SB, Goodwill SR, Haake SJ. Validation of a live, automatic ball velocity and spin rate finder in tennis. In: Procedia Engineering [Internet]. 2010. p. 2967–72. Available from: http://dx.doi.org/10.1016/j.proeng.2010.04.096

205. Ahmadi A, Rowlands D, James DA. Towards a wearable device for skill assessment and skill acquisition of a tennis player during the first serve. Sport Technol. 2010;2(3–4):129–36.

206. Fanchiang H-C, Finch A, Ariel G. Effects of one and two handed tennis backhands hit with varied power levels on torso rotation. ISBS-Conference Proc Arch. 2013;1(1):3–6.

207. Muhamad TA, Rashid AA, Razak MRA, Salamuddin N. A comparative study of backhand strokes in tennis among national tennis players in Malaysia. Procedia - Soc Behav Sci [Internet]. 2011;15:3495–9. Available from: http://dx.doi.org/10.1016/j.sbspro.2011.04.324

208. Fogt N, Persson TW, Vis O, Author S. A Pilot Study of Horizontal Head and Eye Rotations in Baseball Batting HHS Public Access Author manuscript. Optom Vis Sci [Internet]. 2017;94(8):789–96. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5637280/pdf/nihms883003.pdf

209. Lafont D. Gaze Control DURING the hitting phase in Tennis: a Preliminary Study. Int J Perform Anal Sport. 2008;8(1):85–100.

210. Manal K, McClay Davis I, Galinat B, Stanhope S. The accuracy of estimating proximal tibial translation during natural cadence walking: Bone vs. skin mounted targets. Clin Biomech. 2003;18(2):126–31.

211. Duarte JE, Reinkensmeyer DJ. Effects of robotically modulating kinematic variability on motor skill learning and motivation. J Neurophysiol. 2015 Apr;113(7):2682–91.

212. Lees A, Rahnama N. Variability and typical error in the kinematics and kinetics of the maximal instep kick in soccer. Sport Biomech. 2013;12(3):283–92.

213. Bartlett R, Wheat J, Robins M. Is movement variability important for sports biomechanists? Vol. 6, Sports Biomechanics. Taylor & Francis; 2007. p. 224–43.

214. Davids K, Glazier P, Araújo D, Bartlett R. Movement systems as dynamical systems: The functional role of variability and its implications for sports medicine. Vol. 33, Sports Medicine. 2003. p. 245–60.

215. Hiley MJ, Zuevsky V V., Yeadon MR. Is skilled technique characterized by high or low variability? An analysis of high bar giant circles. Hum Mov Sci. 2013;32(1):171–80.

216. Bradshaw EJ, Maulder PS, Keogh JWL. Biological movement variability during the sprint start: Performance enhancement or hindrance? Sport Biomech. 2007;6(3):246–60.

217. Bradshaw EJ, Aisbett B. Visual guidance during competition performance and run-through training in long jumping. Sport Biomech. 2006;5(1):1–14.

218. Whiteside D, Elliott BC, Lay B, Reid M. Coordination and variability in the elite female tennis serve. J Sports Sci [Internet]. 2015;33(7):675–86. Available from: http://dx.doi.org/10.1080/02640414.2014.962569

219. Antúnez R, Hernández F, García J, Vaíllo R, Arroyo J. Relationship between motor variability, accuracy, and ball speed in the tennis serve. J Hum Kinet. 2012;33(1):45–53.

220. Mendes PC, Fuentes Garcia JP, Sousa Mendes RM, Lourenço Martins FM, Batista Clemente FM, Couceiro MS. The variability of the serve toss in tennis under the influence of artificial crosswind. J Sport Sci Med. 2013;12(2):309–15.

221. Sevrez V, Creveaux T, Dumas R, Chèze L, Macé P, Rogowski I. Influence of racket on the variability of humerothoracic joint kinematics during tennis serve: a preliminary study. Comput Methods Biomech Biomed Engin. 2014;17(SUPP1):152–3.

222. Knudson D, Bahamonde R. Effect of endpoint conditions on position and velocity near impact in tennis. J Sports Sci. 2001;19(11):839–44.

223. Yamamoto H, Shinya M, Kudo K. Cognitive Bias for the Distribution of Ball Landing Positions in Amateur Tennis Players (Cognitive Bias for the Motor Variance in Tennis). J Mot Behav. 2019;51(2):141–50.

224. Knudson D V., Blackwell JR. Variability of impact kinematics and margin for error in the tennis forehand of advanced players. Sport Eng. 2005;8(2):75–80.

225. Blackwell J, Knudson D V. Vertical Plane Margins for Error in the Topspin Forehand of Intermediate Tennis Players. Med Sport [Internet]. 2005;9(3):83–6. Available from: http://www.itftennis.com/itn/

226. Wagner H, Pfusterschmied J, Klous M, von Duvillard SP, Müller E. Movement variability and skill level of various throwing techniques. Hum Mov Sci [Internet]. 2012;31(1):78–90. Available from: http://dx.doi.org/10.1016/j.humov.2011.05.005

227. Button C, Macleod M, Sanders R, Coleman S. Examining movement variability in the basketball free-throw action at different skill levels. Res Q Exerc Sport. 2003;74(3):257–69.

228. Whiteside D, Elliott B, Lay B, Reid M. A kinematic comparison of successful and unsuccessful tennis serves across the elite development pathway. Hum Mov Sci. 2013;32(4):822–35.

229. Schorer J, Baker J, Fath F, Jaitner T. Identification of interindividual and intraindividual movement patterns in handball players of varying expertise levels. J Mot Behav. 2007;39(5):409–21.

230. D. W, Lay B, Elliot B, Reid M. The effect of age on variability and coordination in the elite female tennis serve. J Sport Sci. 2013;(29):573–82.

231. Delgado-García G, Vanrenterghem J, Muñoz-García A, Molina-Molina A, Soto-Hermoso VM. Does stroke performance in amateur tennis players depend on functional power generating capacity? J Sports Med Phys Fitness. 2019;59(5):760–6.

232. Tucker CB, Anderson R, Kenny IC. Is outcome related to movement variability in golf? Sport Biomech. 2013;12(4):343–54.

233. Delgado-García G, Vanrenterghem J, Courel-Ibáñez J, Ruiz-Malagon EJ, Ruiz-Alias S, Soto-Hermoso VM. A tennis field test to objectively measure the hitting accuracy based on an Excel spreadsheet: Practical guidelines and applications. Int J Racket Sport Sci. 2019;1(2):24–36.

234. Buzzi UH, Stergiou N, Kurz MJ, Hageman PA, Heidel J. Nonlinear dynamics indicates aging affects variability during gait. Clin Biomech. 2003;18(5):435–43.

235. Sprott JC. Chaos data analyzer (profesional version). Phys Acad Softw;

236. Taylor PG, Landeo R, Coogan J. Intraindividual movement variability within the 5 m water polo shot. J Appl Biomech. 2014;30(3):477–82.

237. Leys C, Ley C, Klein O, Bernard P, Licata L. Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. J Exp Soc Psychol [Internet]. 2013;49(4):764–6. Available from: http://dx.doi.org/10.1016/j.jesp.2013.03.013

238. Evans JD. Straightforward statistics for the behavioral sciences. Pacific Grove: Brooks/Cole; 1996.

239. Friedrich S, Konietschke F, Pauly M. Analysis of Multivariate Data and Repeated Measures Designs with the R Package MANOVA.RM. 2018;

240. Rousseau P, Hoshizaki TB. Defining the effective impact mass of elbow and shoulder strikes in ice hockey. Sport Biomech. 2015 Jan;14(1):57–67.

241. Lees A, Nolan L. Three-dimensional kinematic analysis of the instep kick under speed and accuracy condition. Sci Footb IV. 2002;16–21.
242. Bańkosz Z, Winiarski S. Using Wearable Inertial Sensors to Estimate Kinematic Parameters and Variability in the Table Tennis Topspin Forehand Stroke. Appl Bionics Biomech. 2020;2020.
243. Ilmane N, LaRue J. Modulation of anticipatory postural adjustments in a complex task under different temporal constraints. Motor Control. 2008;12(4):330–47.
244. Kentel BB, King MA, Mitchell SR. Evaluation of a subject-specific, torque-driven computer simulation model of one-handed tennis backhand ground strokes. J Appl Biomech. 2011;27(4):345–54.
245. Lafont D. Gaze Control during the hitting phase in Tennis: a Preliminary Study. Int J Perform Anal Sport. 2008;16.
246. Bahill AT, Laritz T. Why Can't Batters Keep Their Eyes on the Ball? Am Sci. 1984;(June):249–53.
247. Fogt N, Persson TW. A pilot study of horizontal head and eye rotations in baseball batting. Optom Vis Sci. 2017;94(8):789–96.
248. Ripoll H, Bard C, Paillard J. Stabilization of head and eyes on target as a factor in successful basketball shooting. Hum Mov Sci. 1986;5(1):47–58.
249. Fleisig G, Chu Y, Weber A, Andrews J. Variability in baseball pitching biomechanics among various levels of competition. Sport Biomech. 2009;8(1):10–21.
250. Quílez-Maimón A, Rojas-Ruiz FJ, Delgado-García G, Courel-Ibáñez J. The q-pass index: A multifactorial imus-based tool to assess passing skills in basketball. Sensors. 2021;21(13):1–14.
251. Luengo Vaquero C. Actividad físico-deportiva extraescolar en alumnos de primaria. Rev Int Med y ciencias la Act física y el Deport. 2007;7(27):174–84.
252. Lees A. Science and the major racket sports : a review Science and the major racket sports : a review. J Sports Sci. 2008;21(9):707–32.
253. Seçkin AÇ, Ateş B, Seçkin M. Review on Wearable Technology in Sports: Concepts, Challenges and Opportunities. Appl Sci. 2023;13(18).

254. Ruiz-malag EJ, García-Pinillos F, Molina-molina A, Soto-hermoso VM, Ruiz-alias SA. RunScribe Sacral Gait Lab TM Validation for Measuring Pelvic Kinematics during Human Locomotion at Different Speeds. Sensors. 2023;23:1–8.

255. Wagner H, Pfusterschmied J, Klous M, von Duvillard SP, Müller E. Movement variability and skill level of various throwing techniques. Hum Mov Sci. 2012;31(1):78–90.

256. Havlucu H, Bostan I, Coskun A, Özcan O. Understanding the lonesome tennis players: Insights for future wearables. Conf Hum Factors Comput Syst - Proc. 2017;Part F1276:1678–85.

257. Wu G, Van Der Helm FCT, Veeger HEJ, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. J Biomech. 2005;38(5):981–92.

AGRADECIMIENTOS (portada)

8. AGRADECIMIENTOS

Me gustaría expresar mi más profundo agradecimiento *"A todas aquellas personas que han sido la luz en mi camino".*

En primer lugar, deseo destacar la contribución excepcional de mis directores de tesis y mentores, Víctor Manuel Soto Hermoso y Gabriel Delgado García. Sus profundos conocimientos y disposición para compartir su experiencia conmigo desde el principio, sin duda es algo por lo que siempre estaré agradecido. Gracias a ellos, he creado vínculos de trabajo con excepcionales investigadores, al mismo tiempo que magnificas personas: Alejandro Molina Molina, Felipe García Pinillos, Luis Enrique Roche Seruendo, Santiago Castro Infantes, Santiago Alejo Ruiz Alias, Maximiliano Ritacco Real, Jose María Chicano Gutiérrez, Jesús Sánchez Hernández y Juan Carlos Guerrero de Mora. Resalto a los tres últimos ya que sin su ayuda no habría podido desarrollar la aplicación del presente trabajo "Virtual Tennis Coach".

Hago una mención especial a mis padres, sin ellos nada de esto habría sido posible, su apoyo incondicional tanto emocional como económico han sido indispensables a lo largo de toda mi vida, no solo durante el desarrollo de esta tesis. Me han enseñado todos los valores importantes, a trabajar duro y valorar cada pequeña cosa. Concretamente, no puedo pasar por alto que fueron ellos los que me llevaron aquel primer día al club de tenis "El campo" de Priego de Córdoba. Durante años, compartieron conmigo las alegrías de las victorias, la superación de las derrotas y el esfuerzo en cada entrenamiento, lo cual, acabaría forjando mi pasión por el deporte en el que se basa la presente tesis: el tenis.

Finalmente, a todas las personas que, de una manera u otra, han formado parte de este viaje, gracias por iluminar mi camino y ser parte fundamental de este logro académico: mi hermano, mi grupo de amigos de Priego de Córdoba y mi querido "Equipo de campeones" compuesto por: Andrea, Melania, Cora y Álvaro.

Anexos (portada)

9. ANEXOS

9.1. ANEXO 1. CONSENTIMIENTOS INFORMADOS PARA ADULTOS (A) Y MENORES DE EDAD (B).

a)

Universidad de Granada

HOJA de CONSENTIMIENTO informado

Propuesta realizada por el Equipo "HUMAN LAB" del iMUDS, grupo "ERGOLAB (CTS-545)" (Universidad de Granada).

Yo, (nombre y apellidos) ....,
con D.N.I. nº...............................He hablado con el profesional responsable del estudio
....

- He leído la hoja de información que se me ha entregado.
- He podido hacer preguntas sobre el estudio.
- He recibido suficiente información sobre el estudio.
- Comprendo que mi participación es voluntaria.
- Comprendo que puedo retirarme del estudio:
    1. Cuando quiera.
    2. Sin tener que dar explicaciones.
    3. Sin que esto repercuta en mis cuidados médicos.
- Presto libremente mi conformidad para participar en el estudio.
- Las muestras obtenidas en este estudio sólo serán utilizadas para los fines específicos del mismo.

Firma del participante: Firma del investigador responsable:

Fdo:..................... Fdo:....................................

Instituto Mixto Universitario Deporte y Salud (iMUDS), Universidad de Granada – Calle Menéndez Pelayo, s/n, Parque Tecnológico de la Salud (Granada). humanlab@ugr.es / +34 655 95 70 98 / http://www.humanlabugr.com/

Human Lab

iMUDS Instituto Mixto Universitario Deporte y Salud

b)

Universidad de Granada

HOJA de CONSENTIMIENTO informado

Propuesta realizada por el Equipo"HUMAN LAB" del iMUDS, grupo"ERGOLAB (CTS-545)" (Universidad de Granada).

Yo, (nombre y apellidos)..., con D.N.I.
nº...........................en calidad de (relación con el participante)..................................
de (nombre del participante)..
He hablado con el investigador responsable del estudio..
....

- He leído la hoja de información que se me ha entregado.
- He podido hacer preguntas sobre el estudio. /profesional responsable del estudio
- He recibido respuestas satisfactorias a mis preguntas.
- He recibido suficiente información sobre el estudio.
- Comprendo que la participación es voluntaria.
- Comprendo que puede retirarse del estudio:
    1. Cuando quiera.
    2. Sin tener que dar explicaciones.
    3. Sin que esto repercuta en sus cuidados médicos.
- Y presto mi conformidad con que (nombre del participante)..................
  ....participe en este estudio.

Firma del responsable: Firma del investigador responsable:

Fdo:...................... Fdo:.......................................

Instituto Mixto Universitario Deporte y Salud (iMUDS), Universidad de Granada – Calle Menéndez Pelayo, s/n, Parque Tecnológico de la Salud (Granada). humanlab@ugr.es / +34 655 95 70 98 / http://www.humanlabugr.com/

Human Lab iMUDS Instituto Mixto Universitario Deporte y Salud

9.2. ANEXO 2. SOLICITUD DE APROBACIÓN DEL COMITÉ DE ÉTICA DE LA UNIVERSIDAD DE GRANADA

[redacted]

Datos del Investigador/Doctorando:

Nombre y Apellidos: Emilio José Ruiz Malagón		DNI: 20225742-W
Dpto.: Educación Física y Deportiva	Centro/Facultad: Ciencias de la Actividad Física y Deporte	
Puesto/Cargo: Doctorando del programa de Biomedicina		
Dirección: C/ Las Flores; 20; 3º IZQ		
Teléfono: 656644167	Fax: NO	e-mail: emiliorm@correo.ugr.es

Datos del Director/es de la tesis:

Nombre y Apellidos: Víctor Manuel Soto Hermoso		DNI: 24224479-M
Dpto.: Educación Física y Deportiva	Centro/Facultad: Ciencias de la Actividad Física y el Deporte.	
Puesto/Cargo: Catedrático de la Universidad de Granada		
Dirección: Urb. Parque del Cubillas, paseo de los olivos, 26-28; 18220; Albolote (Granada)		
Teléfono: 655957101	Fax: NO	e-mail: vsoto@ugr.es

Datos del Director/es de la tesis:

Nombre y Apellidos:		DNI
Dpto.:	Centro/Facultad:	
Puesto/Cargo:		
Dirección:		
Teléfono:	Fax:	e-mail:

Título de la tesis:	Eficacia del empleo de tecnologías portables para la monitorización de indicadores de rendimiento y salud en tenistas.

INFORMACION SOBRE EL PROTOCOLO EXPERIMENTAL

- Remitir memoria o resumen de la tesis doctoral en formato pdf
- Se recomienda ver y chequear los puntos de la **plantilla de evaluación** y de la **guía rápida** que correspondan en la web del Vicerrectorado de Investigación, Comité de Ética, en la sección de impresos (http://investigacion.ugr.es/pages/etica/impresos), pues sirve de pauta y evita modificaciones y retrasos eludibles.
- **Requiere o solicita informe de otro Comité de Ética**: **Sí**, ~~**No**~~ (***tache lo que proceda***). En caso afirmativo, indique cuál o cuáles ....y adjunte el informe si lo tiene o la solicitud del mismo.

Firma Fecha 12/04/2019

Nombre y apellidos (Investigador responsable) Víctor Manuel Soto Hermoso

Información general del proyecto

Hipótesis y objetivos:

Sostenemos la hipótesis de que nuestro novedoso sistema de asesor virtual de tenis mejorará el proceso de enseñanza-aprendizaje en una muestra de jugadores que se encuentren en la fase de adquisición de la técnica de golpeo. Ya que se ha demostrado que existen patrones biomecánicos que determinan los distintos tipos de golpeo en tenis y el nivel del jugador. Además, creemos que dichos patrones biomecánicos pueden estar relacionadas con variables fisiológicas como la frecuencia cardiaca, consumo de oxígeno o el índice de saturación de tejidos y que dicha información nos podría permitir reducir el riesgo de lesiones musculo-esqueléticas al mismo tiempo que optimizamos el rendimiento y el aprendizaje del tenista.

El objetivo principal de la presente tesis es diseñar, implementar y validar un sistema tecnológico basado en asesores virtuales y wearables, gracias al cual podremos evaluar variables biomecánicas, fisiológicas, así como optimizar el proceso de enseñanza-aprendizaje de nuestro tenista en situación real de juego.

Material y método:

Se utilizarán métodos que no implican riesgo sobre la salud humana o la preparación física del deportista. Se obtendrán variables de las siguientes temáticas:

- Variables Biomecánicas: aceleraciones, rotaciones, angulación de partes del cuerpo humano durante la práctica del tenis mediante tecnologías portables no invasivas.
- Variables fisiológicas: antropometría, composición corporal y parámetros cardiovasculares mediante tecnologías portables no invasivas.
- Variables Psicosociales y procesos de enseñanza-aprendizaje.
- Test específico de golpeo (Lions et al., 2013): se analiza la técnica, la potencia, la precisión y la fatiga asociada usando tecnologías avanzadas (máquina lanzapelotas, radar de alta gama, cámaras de alta velocidad, sensor inercial para determinar la localización del impacto en la raqueta, pulsometros).

Todos estos test se basan en la literatura científica más actual para asegurar la transferencia al deporte de raqueta en cuestión. Algunos de ellos se realizan en federaciones de tenis de importancia a nivel internacional como la española, la americana o la alemana.

Estudio previo de tenis de mi grupo de investigación: Delgado-García, G., Vanrenterghem, J., Muñoz-García, A., Molina-Molina, A., & Soto-Hermoso, V. M. (2018). Does stroke performance in amateur tennis players depend on functional power generating capacity? *The Journal of sports medicine and physical fitness.*

Beneficios derivados del estudio

Generaremos un informe personalizado donde se reflejarán los resultados más destacados de las variables anteriormente citadas. Este informe incluirá detección de factores de riesgo y recomendaciones para optimización de la técnica de golpeo.

Incomodidades derivadas del estudio

La información obtenida cumple los principios éticos para investigaciones médicas en humanos. Además, las pruebas que se realizarán a los participantes serán submáximas no suponiendo ningún riesgo para su salud.

Posibles acontecimientos adversos

No se prevén acontecimientos adversos que impliquen peligrosidad sobre la salud para los sujetos de estudio de la presente tesis doctoral.

Voluntariedad

El participante lo hace de forma voluntaria, pudiéndose retirar del estudio en cualquier momento. Podrá además solicitar que sus datos sean eliminados de la base de datos.

Protección de datos

Se cumplirán las normas de la Declaración de Helsinki (1989), las recomendaciones de Buena Práctica Clínica de la CEE (1990) y el Real Decreto 561/1993 sobre ensayos clínicos. Los resultados obtenidos serán registrados en formato digital y almacenados empleando metodologías de encriptación y protección de datos.

Responsable: Emilio José Ruiz Malagón, Telf.: 656644167; e-mail: emiliorm@correo.ugr.es

9.3. ANEXO 3. INSTRUCCIONES DE PARTICIPACIÓN EN EL PRESENTE PROYECTO

INSTRUCCIONES para PARTICIPAR en el PROYECTO

Propuesta realizada por el grupo "HUMAN LAB" del iMUDS

Para la evaluación, los participantes deben venir "preparados", lo cual implica el cumplimiento de las siguientes **INSTRUCCIONES**, muchas de ellas relacionadas con la **INDUMENTARIA**:

- **CALENDARIO**: la evaluación se realizará el próximo**___________**. Cada participante será citado previamente.
- **LUGAR:** las pruebas se realizarán en el iMUDS (Instituto Mixto Universitario Deporte y Salud), en Calle Menéndez Pelayo, nº32. Centro situado dentro del Parque Tecnológico de la Salud (PTS).
- Consideraciones para la prueba de **COMPOSICIÓN COPORAL:**

Debe acudir al lugar de evaluación, como mínimo, 2 horas después de haber realizado su última comida. En las 24 h previas no realizar esfuerzos físicos intensos.

No llevar consigo accesorios metálicos (anillos, pulseras, colgantes).

Una vez terminada esta prueba puede comer.

- Consideraciones para el **RESTO DE PRUEBAS** (condición física, podología, marcha, carrera, etc):

Se empleará ropa deportiva "CÓMODA", recomendándose camiseta corta o de tirantes, y malla o pantalón corto. Para los momentos de descanso, es conveniente traer algo para merendar y líquidos para hidratarse (agua, zumo, bebida isotónica, etc.). El centro dispone de agua potable, y máquinas de refrescos y snack.

CALZADO: deportivo (no de caña alta). Se empleará el calzado deportivo que el usuario considere más confortable para la realización de todas las pruebas de condición física y de locomoción: andar, correr, saltos, pruebas de agilidad. Se empleará el calzado que cada usuario considere adecuado para cada prueba.

Responsable: Emilio José Ruiz Malagón; Telf.: 656644167; e-Mail: emiliorm@correo.ugr.es

9.4. ANEXO 4. DOCUMENTO DE APROBACIÓN EXPERIMENTACIÓN CON HUMANOS DE LA PRESENTE TESIS (COMITÉ DE ÉTICA DE LA UNIVERSIDAD DE GRANADA).

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: 'EFICACIA DEL EMPLEO DE TECNOLOGíAS PORTABLES PARA LA MONITORIZACIóN DE INDICADORES DE RENDIMIENTO Y SALUD EN TENISTAS.' que dirige D./Dña. EMILIO JOSé RUIZ MALAGóN, con NIF 20.225.742-W, quedando registrada con el nº: 912/CEIH/2019.

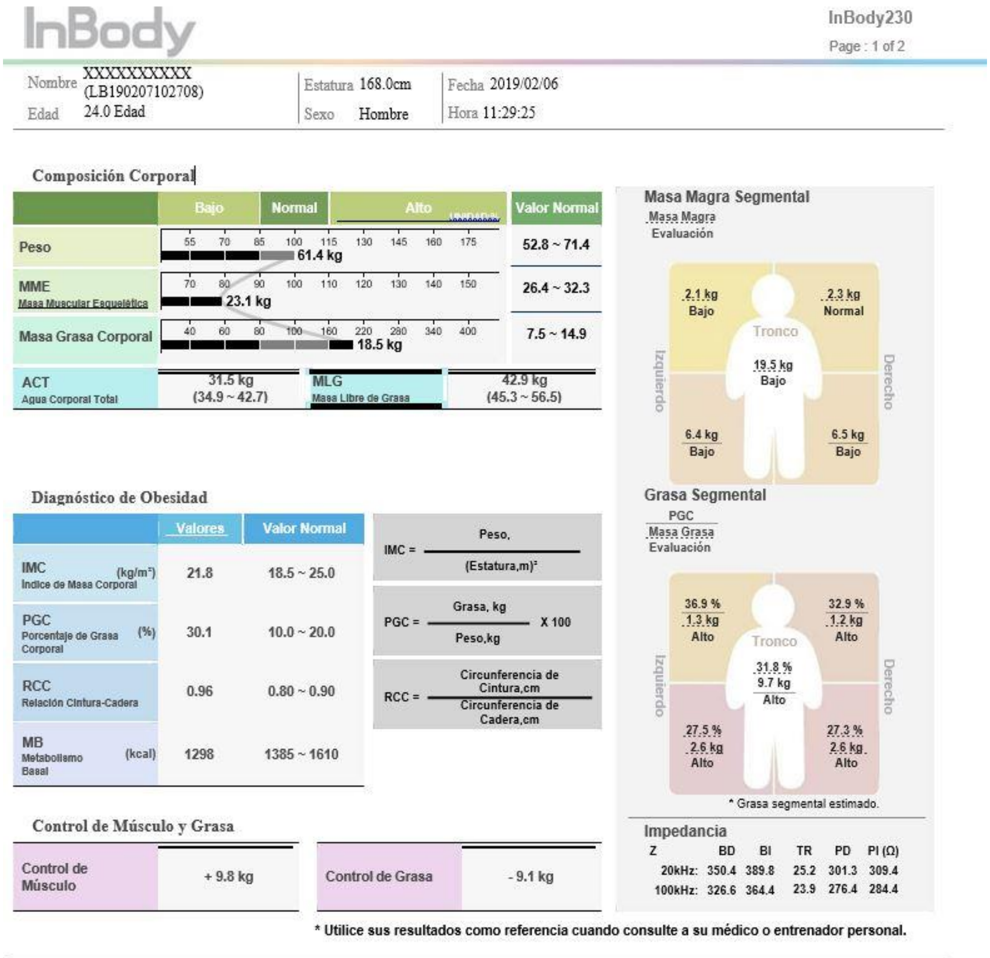
Granada, a 30 de Septiembre de 2019.

EL PRESIDENTE
Fdo: Enrique Herrera Viedma

EL SECRETARIO
Fdo: Fernando Cornet Sánchez del Águila

Gran Vía de Colón 48, 2 Planta. 18071 GRANADA
http://investigacion.ugr.es

9.5. ANEXO 5. EJEMPLO DE INFORME DE COMPOSICIÓN CORPORAL ENTREGADO A LOS PARTICIPANTES DE LOS DISTINTOS ESTUDIOS



InBody — InBody230 — Page : 1 of 2

Nombre	XXXXXXXXXX (LB190207102708)	Estatura 168.0cm	Fecha 2019/02/06
Edad	24.0 Edad	Sexo Hombre	Hora 11:29:25

Composición Corporal

	Bajo	Normal	Alto	Valor Normal
Peso	55 70 85 100 115 130 145 160 175	61.4 kg		52.8 ~ 71.4
MME Masa Muscular Esquelética	70 80 90 100 110 120 130 140 150	23.1 kg		26.4 ~ 32.3
Masa Grasa Corporal	40 60 80 100 160 220 280 340 400	18.5 kg		7.5 ~ 14.9

ACT Agua Corporal Total	31.5 kg (34.9 ~ 42.7)	MLG Masa Libre de Grasa	42.9 kg (45.3 ~ 56.5)

Masa Magra Segmental

Masa Magra / Evaluación

	Izquierdo	Tronco	Derecho
Brazo	2.1 kg Bajo	19.5 kg Bajo	2.3 kg Normal
Pierna	6.4 kg Bajo		6.5 kg Bajo

Diagnóstico de Obesidad

	Valores	Valor Normal
IMC (kg/m²) Índice de Masa Corporal	21.8	18.5 ~ 25.0
PGC (%) Porcentaje de Grasa Corporal	30.1	10.0 ~ 20.0
RCC Relación Cintura-Cadera	0.96	0.80 ~ 0.90
MB (kcal) Metabolismo Basal	1298	1385 ~ 1610

$$IMC = \frac{Peso,}{(Estatura,m)^2}$$

$$PGC = \frac{Grasa, kg}{Peso,kg} \times 100$$

$$RCC = \frac{Circunferencia\ de\ Cintura,cm}{Circunferencia\ de\ Cadera,cm}$$

Grasa Segmental

PGC / Masa Grasa / Evaluación

	Izquierdo	Tronco	Derecho
Brazo	36.9 % 1.3 kg Alto	31.8 % 9.7 kg Alto	32.9 % 1.2 kg Alto
Pierna	27.5 % 2.6 kg Alto		27.3 % 2.6 kg Alto

* Grasa segmental estimado.

Control de Músculo y Grasa

Control de Músculo	+ 9.8 kg	Control de Grasa	- 9.1 kg

Impedancia

Z	BD	BI	TR	PD	PI (Ω)
20kHz:	350.4	389.8	25.2	301.3	309.4
100kHz:	326.6	364.4	23.9	276.4	284.4

* Utilice sus resultados como referencia cuando consulte a su médico o entrenador personal.

9.6. ANEXO 6. MATERIAL SUPLEMENTARIO *ESTUDIO 3.*

- Supplementary file: Justification of the Cardan sequence selection with examples

In a pilot study five tennis players performed a series of forehands at 500 Hz that were filtered at 18 Hz (more details on the selection of the cutoff filter are given in the main study). The elbow angles of the NOTCH® sensor (flexion-extension and pronation-supination) were compared with those obtained with the MOCAP 3D system (Qualisys + Visual 3D). The main study explains the procedure for placing the NOTCH sensors and the reflective markers and the reconstruction of the 3D coordinate axes of the arm and forearm segments. To calculate 3D angles using Visual 3D, initially we use the Cardan sequence ML-AP-AXIAL as recommended by the ISB (257). The first rotation (ML) refers to flexion and the third rotation (AXIAL) to pronation of the forearm. The visual inspection of the signal showed a great similarity between the value of the first rotation of the Cardan sequence ML-AP-AXIAL and the elbow flexion angle indicated by the Notch device (see Supplementary Figure 33a, 33c, 33e, 33g and 33i). There was a vertical offset between both signals that was easily corrected by adding or subtracting a constant value to the elbow angle signal computed with the MOCAP based on the cross-correlation between both signals (159). Supplementary table 12 shows the value off this offset for each subject and each condition of the experiment explained in the main document. However, in the case of the pronosupination computed by the IMU NOTCH when we inspect visually the superimposed signal with that of the third rotation of the Cardan sequence ML-AP-AXIAL, there was almost any similarity. We then tried to compare the signal from the second rotation of the Cardan sequence ML-AP-AXIAL with the pronosupination (we hypothesized that there could be an error in the internal algorithms of the NOTCH® sensor). We didn't see any similarities either. So, we decided to compare the signals with other rotations, using different Cardan sequences and we noticed that there was a strong resemblance - the peaks and valleys of the signal coincided in many cases - with the first rotation of the AP-AXIAL-ML Cardan sequence. We corrected the temporal offset by translating the signal to the right or to the left (using an Excel application designed ad hoc), using a cross-correlation based phase shift technique (159). There was a small offset in terms of the initial angle (due to differences between the coordinates axis of the arm and forearm of the NOTCH® sensor and MOCAP System) that we corrected by adding or subtracting a constant value to the elbow angle signal computed by the MOCAP 3D. Finally, although the two signals had the same trend (there was a large coincidence in time between the peaks and valleys of both) we had to apply a scale compression factor to the elbow angle computed by the MOCAP. These two transformations of the signal (adding or subtracting a constant value and using a scale compression factor) were also based on the cross-correlation between both signals. Supplementary table 13 shows the values of the constant assessment that was added or subtracted and of the scale factor for each of the subjects and each of the series explained in the main document. Supplementary figure 33b, 33d, 33f, 33h and 33j show the similarities between the transformed signals (first rotation of the Cardan sequence AP-AXIAL-ML) and the pronosupination angle computed by the NOTCH® sensors.

As can be seen in the table 12 and 13, both the offset of the 1st rotation Cardan sequence ML-AP-AXIAL, the offset of the 1st rotation Cardan sequence AP-AXIAL-ML and the scale factor applied to the 1st rotation Cardan sequence AP-AXIAL -ML were very similar at the within-subject level (mean and total standard deviation were 22.1 ± 12.7; 111 ± 44.7 and 1.7 ± 0.4). It seems that in the case of flexo-extension the offset appears to be 26 degrees. In the case of pronosupination the offset seems larger (close to 100 degrees in most cases) and a scale factor of approximately 1.6 must also be applied.

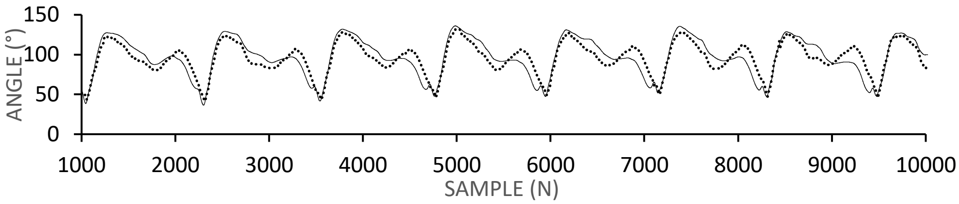
Table 12. Shows the values of the constant assessment that was added or subtracted and of the scale factor for each of the subjects

Participant (S), condition (PRE or POST) and sampling rate (Hz)	Value added or subtracted (offset) in degrees		Scale factor applied to the 1st rotation Cardan sequence AP-AXIAL-ML	Participant, condition and sampling rate	Value added or subtracted (offset) in degrees		Scale factor applied to the 1st rotation Cardan sequence AP-AXIAL-ML	Participant (S), condition (PRE or POST) and sampling rate (Hz)	Value added or subtracted (offset) in degrees		Scale factor applied to the 1st rotation Cardan sequence AP-AXIAL-ML
	1st rotation Cardan sequence ML-AP-AXIAL	1st rotation Cardan sequence AP-AXIAL-ML			1st rotation Cardan sequence ML-AP-AXIAL	1st rotation Cardan sequence AP-AXIAL-ML			1st rotation Cardan sequence ML-AP-AXIAL	1st rotation Cardan sequence AP-AXIAL-ML	
S1_PRE_500	28	95	1.4	S6_PRE_500	20	70	2.3	S11_PRE_500	19	101	1.7
S1_PRE_250	27	91	1.4	S6_PRE_250	17	97	3.1	S11_PRE_250	28	95	1.7
S1_PRE_100	37	106	1.4	S6_PRE_100	19	76	2.9	S11_PRE_100	29	94	1.5
S1_POST_500	-5	95	1.7	S6_POST_500	17	101	3	S11_POST_500	20	116	1.8
S1_POST_250	18	80	1.4	S6_POST_250	17	74	2.4	S11_POST_250	21	108	1.7
S1_POST_100	28	94	1.4	S6_POST_100	25	75	2.4	S11_POST_100	35	126	1.8
S2_PRE_500	52	124	1.4	S7_PRE_500	23	129	2	S12_PRE_500	23	117	1.7
S2_PRE_250	52	134	1.5	S7_PRE_250	21	150	2.3	S12_PRE_250	26	150	2.1
S2_PRE_100	19	108	1.5	S7_PRE_100	24	95	1.4	S12_PRE_100	26	114	1.7
S2_POST_500	51	128	1.5	S7_POST_500	19	112	1.9	S12_POST_500	27	118	1.7
S2_POST_250	52	135	1.5	S7_POST_250	20	99	1.5	S12_POST_250	27	107	1.6
S2_POST_100	50	122	1.4	S7_POST_100	23	96	1.5	S12_POST_100	26	119	1.7
S3_PRE_500	35	108	1.4	S8_PRE_500	21	92	1.8	S13_PRE_500	16	87	1.6
S3_PRE_250	31	110	1.4	S8_PRE_250	24	102	1.9	S13_PRE_250	15	95	1.4
S3_PRE_100	25	114	1.4	S8_PRE_100	25	70	1.4	S13_PRE_100	17	86	1.5
S3_POST_500	34	124	1.5	S8_POST_500	23	86	1.7	S13_POST_500	17	83	1.5
S3_POST_250	29	118	1.5	S8_POST_250	23	85	1.7	S13_POST_250	17	79	1.5
S3_POST_100	28	128	1.5	S8_POST_100	28	102	1.8	S13_POST_100	19	95	1.4

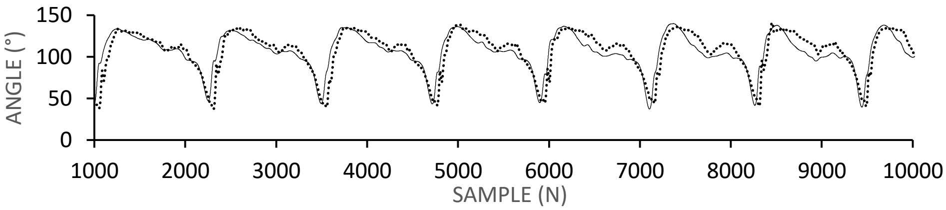
Table 13. Shows the values of the constant assessment that was added or subtracted and of the scale factor for each of the subjects

Participant (S), condition (PRE or POST) and sampling rate (Hz)	Value added or subtracted (offset) in degrees		Scale factor applied to the 1st rotation Cardan sequence AP-AXIAL-ML	Participant (S), condition (PRE or POST) and sampling rate (Hz)	Value added or subtracted (offset) in degrees		Scale factor applied to the 1st rotation Cardan sequence AP-AXIAL-ML	Participant (S), condition (PRE or POST) and sampling rate (Hz)	Value added or subtracted (offset) in degrees		Scale factor applied to the 1st rotation Cardan sequence AP-AXIAL-ML
	1st rotation Cardan sequence ML-AP-AXIAL	1st rotation Cardan sequence AP-AXIAL-ML			1st rotation Cardan sequence ML-AP-AXIAL	1st rotation Cardan sequence AP-AXIAL-ML			1st rotation Cardan sequence ML-AP-AXIAL	1st rotation Cardan sequence AP-AXIAL-ML	
S4_PRE_500	25	119	1.4	S9_PRE_500	16	189	2.4	S14_PRE_500	-15	130	1.5
S4_PRE_250	26	143	1.7	S9_PRE_250	16	161	2.2	S14_PRE_250	-14	87	1
S4_PRE_100	28	156	1.6	S9_PRE_100	16	123	2.1	S14_PRE_100	31	158	1.7
S4_POST_500	26	152	1.7	S9_POST_500	4	131	2	S14_POST_500	20	169	1.7
S4_POST_250	28	193	2.1	S9_POST_250	17	157	2.1	S14_POST_250	17	149	1.5
S4_POST_100	21	310	2.6	S9_POST_100	13	134	1.9	S14_POST_100	30	148	1.5
S5_PRE_500	0	-148	1.4	S10_PRE_500	7	181	2	S15_PRE_500	33	73	1.6
S5_PRE_250	-3	95	1.4	S10_PRE_250	21	131	1.6	S15_PRE_250	32	70	1.5
S5_PRE_100	-2	95	1.4	S10_PRE_100	19	130	1.5	S15_PRE_100	34	74	1.4
S5_POST_500	-1	95	1.4	S10_POST_500	22	129	1.6	S15_POST_500	33	78	1.6
S5_POST_250	0	95	1.4	S10_POST_250	17	110	1.5	S15_POST_250	31	69	1.5
S5_POST_100	-3	95	1.4	S10_POST_100	19	118	1.4	S15_POST_100	36	77	1.6

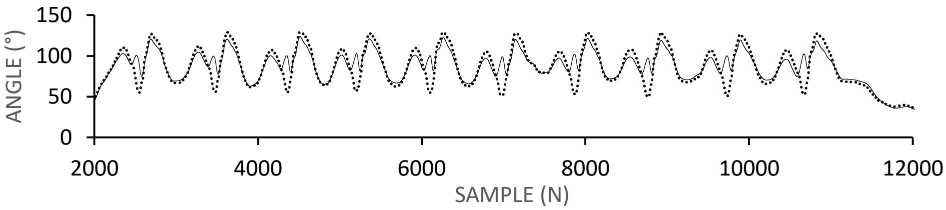
a) Participant number 3. First rotation Cardan sequence ML-AP-AXIAL vs. Flexo-extension Notch® (RMSE = 8.73)



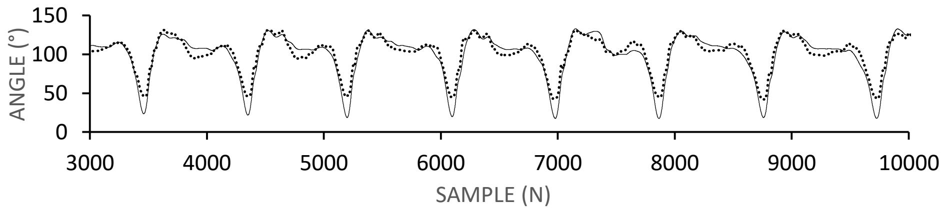
b) Participant number 3. First rotation Cardan sequence AP-AXIAL-ML vs. Pronation-supination Notch® (RMSE = 8.73). Scale factor = 1 / 1.4



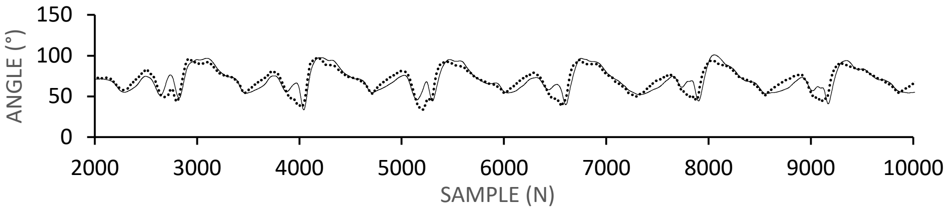
c) Participant number 4. First rotation Cardan sequence ML-AP-AXIAL vs. Flexion-extension Notch® (RMSE = 2.71)



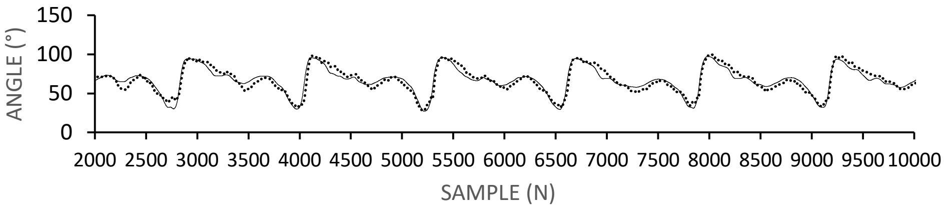
d) Participant number 4. First rotation Cardan sequence AP-AXIAL-ML vs. Pronation-supination Notch® (RMSE = 8.92). Scale factor = 1.4



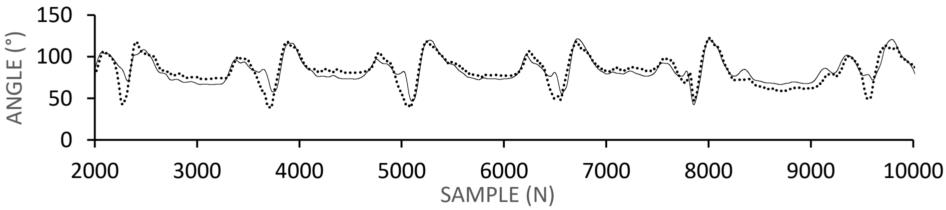
e) Participant number 8. First rotation Cardan sequence ML-AP-AXIAL vs. Flexion-extension Notch® (RMSE = 6.75)



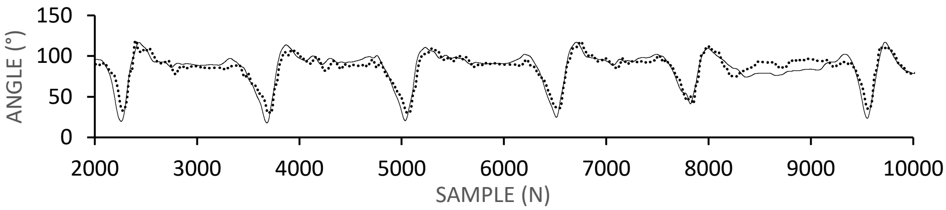
f) Participant number 8. First rotation Cardan sequence AP-AXIAL-ML vs. Pronation-supination Notch® (RMSE = 6.85). Scale factor = 1.8



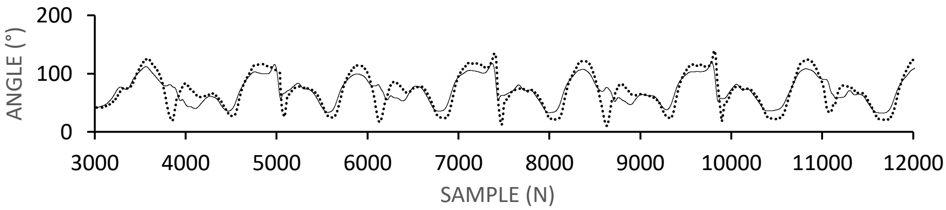
g) Participant number 12. First rotation Cardan sequence ML-AP-AXIAL vs. Flexion-extension Notch® (RMSE = 8.78)



h) Participant number 12. First rotation Cardan sequence AP-AXIAL-ML vs. Pronation-supination Notch® (RMSE = 7.99). Scale factor = 1.7



i) Participant number 15. First rotation Cardan sequence ML-AP-AXIAL vs. Flexion-extension Notch® (RMSE = 8.78)



j) Participant number 15. First rotation Cardan sequence AP-AXIAL-ML vs. Pronation-supination Notch® (RMSE = 3.78). Scale factor = 1.6

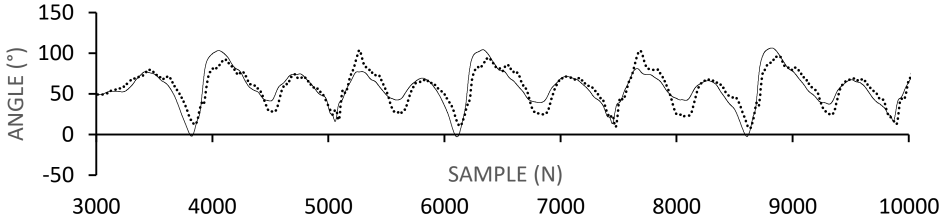


Figure 33. Superposition of the elbow angle signal obtained with the MOCAP system and with the NOTCH sensor in the case of 5 subjects. The elbow angle signals with the MOCAP system have been transformed as explained in the initial text of this document

9.7. ANEXO 7. CURRÍCULO DE EMILIO J. RUIZ-MALAGÓN, AUTOR DEL TRABAJO.

Parte A. DATOS PERSONALES

Fecha del CVA	15/12/2023

Nombre y apellidos	Emilio José Ruiz Malagón		
DNI/NIE/pasaporte	20225742-W	Edad	31
Núm. identificación	WoS Researcher ID	AAD-1597-2021	
	Open Researcher and Contributor ID (ORCID)	https://orcid.org/0000-0003-1228-5413	

A.1. *Situación profesional actual*

Organismo	Universidad de Granada		
Dpto./Centro	Departamento de Educación Física y Deportiva		
Dirección	Carretera de Alfacar, s/n, 18011, Granada, España.		
Teléfono	+34656644167	correo electrónico	emiliorm@ugr.es
Categoría profesional	Estudiante de doctorado	Fecha inicio	01/09/2019
Palabras clave	Biomecánica; rendimiento; wearables; análisis 3D; deportes de raqueta.		

A.2. *Formación académica*

Titulación	Universidad / Institución	Año
Grado de Educación Primaria con Mención en Educación Física.	Universidad de Granada	2013-2017
Máster de Investigación en Actividad Física y Deporte.	Universidad de Granada	2017-2018

A.3. *Indicadores generales de calidad de la producción científica*
Publicaciones totales: 16; **JCR:** 12
Citas totales: 120**; H-Index:** 5; **Índice i10:** 4
Media de Citas/año: 19 (Web of Science)

Parte B. RESUMEN LIBRE DEL CURRÍCULUM

Actualmente matriculado en el programa de doctorado en biomedicina de la Universidad de Granada. Mi principal línea de investigación es la biomecánica aplicada a la marcha, locomoción y deportes de raqueta, mediante el uso de tecnologías portables (wearables). Investigador a tiempo completo en el Instituto Mixto Universitario de Deporte y Salud (IMUDS) perteneciente a la Universidad de Granada. Jugador de tenis de competición y amante del deporte en general, lo que provocó mi traslado de la facultad de Ciencias de la Educación a la de Ciencias de la Actividad Física y el Deporte para realizar mis estudios de posgrado.

Parte C. MÉRITOS MÁS RELEVANTES

C.1. *Publicaciones incluidas en la tesis*

1. Ruiz-Malagón, E. J., Delgado-García, G., Castro-Infantes, S., Ritacco-Real, M., & Soto-Hermoso, V. M. (2022). Validity and reliability of NOTCH® inertial sensors for measuring elbow joint angle during tennis forehand at different sampling frequencies. *Measurement*, *201*, 111666.
2. Ruiz-Malagón, E. J., Castro-Infantes, S., Ritaco-Real, M., & Soto-Hermoso, V. M. (2023). Concurrent validity of the Polar Precision Prime® photoplethysmographic system to measure heart rate during a tennis training session. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 17543371231165102.
3. Ruiz-Malagón, E. J., Delgado-García, G., Ritacco-Real, M., & Soto-Hermoso, V. M. (2022). Kinematics differences between one-handed and two-handed tennis backhand using gyroscopes. An exploratory study. *International Journal of Racket Sports Science*, *4*(1), 16-24.
4. Ruiz-Malagón, E. J., Vanrenterghem, J., Ritacco-Real, M., González-Fernández, F. T., Soto-Hermoso, V. M., & Delgado-García, G. (2023). Field-based upper-body motor variability as determinant of stroke performance in the main tennis strokes. *Proceedings of the Institution*

of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 17543371231156266.

***C.2.** Otras publicaciones del autor no incluidas en la tesis*

1. Delgado-García, G., Vanrenterghem, J., Courel-Ibáñez, J., **Ruiz-Malagón, E. J**., Ruiz-Alias, S., & Soto-Hermoso, V. M. (2019). A tennis field test to objectively measure the hitting accuracy based on an Excel spreadsheet. *International Journal of Racket Sports Science*, *1*(2), 24-36.
2. Delgado-García, G., Vanrenterghem, J., Muñoz-García, A., **Ruiz-Malagón, E. J**., Mañas-Bastidas, A., & Soto-Hermoso, V. M. (2019). Probabilistic structure of errors in forehand and backhand groundstrokes of advanced tennis players. *International Journal of Performance Analysis in Sport*, *19*(5), 698-710
3. García-Pinillos, F., Chicano-Gutiérrez, J. M., **Ruiz-Malagón, E. J**., & Roche-Seruendo, L. E. (2020). Influence of RunScribe™ placement on the accuracy of spatiotemporal gait characteristics during running. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *234*(1), 11-18.
4. **Ruiz-Malagón, E. J.,** Ruiz-Alias, S. A., García-Pinillos, F., Delgado-García, G., & Soto-Hermoso, V. M. (2020). Comparison between photoplethysmographic heart rate monitor from Polar Vantage M and Polar V800 with H10 chest strap while running on a treadmill: Validation of the Polar Precision PrimeTM photoplestimographic system. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 1754337120976659.
5. García-Pinillos, F., Latorre-Román, P. A., Chicano-Gutiérrez, J. M., **Ruiz-Malagón, E. J.,** Párraga-Montilla, J. A., & Roche-Seruendo, L. E. (2020). Absolute reliability and validity of the OptoGaitTM system to measure spatiotemporal gait parameters during running. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 1754337120977409.
6. Molina-Molina, A.; **Ruiz-Malagón, E.J**.; Carrillo-Pérez, F.; Roche-Seruendo, L.E.; Damas, M.; Banos, O.; García-Pinillos, F., (2020). Validation of mDurance, A Wearable Surface Electromyography System for Muscle Activity Assessment. *Frontiers in Physiology 11*, 606287.
7. Delgado-García, G., Vanrenterghem, J., **Ruiz-Malagón, E. J**., Molina-García, P., Courel-Ibáñez, J., & Soto-Hermoso, V. M. (2020). IMU

gyroscopes are a valid alternative to 3D optical motion capture system for angular kinematics analysis in tennis. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 1754337120965444.

8. Ruiz-Alias, S. A., García-Pinillos, F., Soto-Hermoso, V. M., & **Ruiz-Malagón, E. J.** (2021). Heart rate monitoring of the endurance runner during high intensity interval training: Influence of device used on training functions. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology,* 17543371211037035.

9. Jaén-Carrillo, D., Ruiz-Alias, S. A., Chicano-Gutiérrez, J. M., **Ruiz-Malagón, E. J.**, Roche-Seruendo, L. E., & García-Pinillos, F. (2022). Test-Retest Reliability of the MotionMetrix Software for the Analysis of Walking and Running Gait Parameters. *Sensors*, *22*(9), 3201.

10. Delgado-García, G., Coll, J. S., Infantes, S. C., **Ruiz-Malagón, E. J**. R., Colio, B. B., & Fernández, F. T. G. (2022). Validation of wearables for technical analysis of tennis players. *International Journal of Racket Sports Science*, *4*(2), 56-60.

11. **Ruiz-Malagón, E. J**., García-Pinillos, F., Molina-Molina, A., Soto-Hermoso, V. M., & Ruiz-Alias, S. A. (2023). RunScribe Sacral Gait Lab™ Validation for Measuring Pelvic Kinematics during Human Locomotion at Different Speeds. *Sensors*, *23*(5), 2604.

12. Ruiz-Malagón, E. J., Delgado-García, G., López-Gutiérrez, E., Zurita-Ortega, F., & Soto-Hermoso, V. M. (2020). Benefits of an intervention programme with racket sports in primary school students. *International Journal of Racket Sports Science*, *2*(2), 9-17.

C.3. *Contratos I+D+i*

1. **“**Exoesqueleto pasivo adaptado a la bota” (ExoBoot). Ref. 10032/18/0053/00 (2018/ SP03390102/00000158). Proyecto financiado por el Ministerio de Defensa de España. SEDEF Dirección General de Armamento y Material. Financiación recibida: 6000 €. Duración: 4 meses (2018-2019). IP: Víctor Manuel Soto Hermoso

2. “Innovación y transferencia de las nuevas tecnologías aplicadas al deporte en la formación profesional” (acrónimo: TICsDeportivasFP). Ref.: Ref. IAFP21/00141. Convocatoria 2021 de ayudas destinadas a la realización de proyectos de innovación e investigación aplicada y transferencia del conocimiento en la Formación Profesional.

Ministerio de Educación y Formación Profesional. Duración: 3 meses (2021). Financiación recibida: 4500 €. IP: Víctor Manuel Soto Hermoso.

3. “Desarrollo, testeo e implantación de un sistema informático que dé soporte al Plan Andaluz de Prescripción de Actividad y Ejercicio Físico” (acrónimo: ActiVital). Entidad financiadora: Junta de Andalucía, a través de un Convenio Específico entre la Consejería de Turismo, Cultura y Deporte de la Junta de Andalucía, y la Universidad de Granada, con cargo a los fondos europeos (NextGenerationEU) del Plan de Recuperación, Transformación y Resiliencia. Las actuaciones objeto de este convenio se desarrollan por miembros del Instituto Mixto Universitario Deporte y Salud (iMUDS). Duración: 6 mese (2023). Financiación recibida: 13.000 €. IP: Víctor Manuel Soto Hermoso.

C.3. *Proyectos I+D+i*

1. “Desarrollo de asesores virtuales y su validación en un proyecto educativo integral para población deportista de bachillerato, formación profesional y universitaria involucrados en formación dual” (EduSport). Ref. PID2020-115600RB-C21. Plan Estatal de I+D+i, convocatoria Retos. Funding received: 36,421 €. Duration: 3 years (2021-2024). IP: Víctor Manuel Soto Hermoso; Co-IP: Felipe García Pinillos.
2. **“**Desarrollo de un prototipo de exoesqueleto pasivo adaptado a bota técnica, para la optimización de la locomoción humana, válido para el ámbito militar y civil **(**ExoLimb2)”. Ref.5974. Convocatoria 2017 de Ayudas a Actividades de Transferencia de Conocimiento entre los Agentes del Sistema Andaluz del Conocimiento y el Tejido Productivo, Plan Andaluz de I+D+I (PAIDI 2020). Financiación: 90,000 €. Duración: 1 año (2019-2020). IP: Víctor Manuel Soto Hermoso.
3. **“**Equipamiento avanzado para investigación orientada hacia el desarrollo del concepto de smart cities/healthy cities en el Instituto Mixto Universitario Deporte y Salud”. Ref. EQC2018-004702-P. Plan Estatal de I+D+i, Ayudas para la Adquisición de Equipamiento Científico-Técnico. Financiación: 826,125 €. Duración: 3 años (2018-2020). IP: Víctor Manuel Soto Hermoso.
4. “Desarrollo de una plataforma digital que permita monitorizar indicadores de rendimiento y salud deportiva para población andaluza involucrada en deporte federado y en programas de ejercicio físico saludable (acrónimo: AndaMove). Ref.: EXP_74829. Entidad

financiadora: Convocatoria de Ayudas para Proyectos de Investigación en Ciencia y Tecnología aplicada a la Actividad Física Beneficiosa para la Salud (AFBS) y la Medicina Deportiva", con cargo a los fondos europeos (NextGenerationEU) del Plan de Recuperación, Transformación y Resiliencia para el año 2022. Organismo: Consejo Superior de Deportes, Ministerio de Cultura y Deporte. Financiación: 155,999 €. Fecha y duracion: desde la fecha de resolución definitiva (27-marzo -2023) hasta el 30-noviembre-2023 (8 meses). IP: Víctor Manuel Soto Hermoso.

5. "Desarrollo, testeo e implantación de un sistema informático que dé soporte al Plan Andaluz de Prescripción de Actividad y Ejercicio Físico" (acrónimo: Andalucía Muévete). Entidad financiadora: Junta de Andalucía, a través de un Convenio Específico entre la Consejería de Turismo, Cultura y Deporte de la Junta de Andalucía, y la Universidad de Granada, con cargo a los fondos europeos (NextGenerationEU) del Plan de Recuperación, Transformación y Resiliencia. Las actuaciones objeto de este convenio se desarrollan por miembros del Instituto Mixto Universitario Deporte y Salud (iMUDS). Financiación: 400,000 €. Fecha y duracion: desde enero de 2023, hasta diciembre de 2023 (12 meses, 1 año). IP (inv. principal): Víctor Manuel Soto Hermoso.

6. "Optimización de la eficiencia de un exoesqueleto pasivo para la locomoción del soldado de tierra" (acrónimo: ExoSoldier). Ref.: CEMIX 9/18. Entidad financiadora: Convocatoria de Proyectos de Investigación del Centro Mixto Universidad de Granada y el Mando de Adiestramiento y Doctrina del Ejército de Tierra Español (CEMIX UGR-MADOC). Financiación: 7,000 €. Fecha y duracion: 1 año, desde el 11-abril-2018 al 11-mayo-2019. IP (inv. principal): Víctor Manuel Soto Hermoso.

7. "Monitorización y fomento de hábitos saludables, mediante una plataforma basada en sensores portables y asesores virtuales, para la promoción del envejecimiento activo en población activa y mayor" (acrónimo: AVISaMe). Ref.: DEP2015-70980-R. Entidad financiadora: Convocatoria de Proyectos de Investigación del Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad, en el marco del Plan Estatal de Investigación Científica y Técnica y de Innovación 2013-2016. Área Temática de Gestión: Deporte. Este proyecto está cofinanciado por el Fondo Europeo de Desarrollo Regional (FEDER). Financiación: 102,850 €. Fecha y duracion: 3 años, desde 1-enero-2016 hasta 31-diciembre-2018 (nos han concedido una prórroga de 1 año extra, hasta el 31-diciembre-

2019). IP (inv. principal) 1: Víctor Manuel Soto Hermoso. Co-IP (inv. principal) 2: Manuel Noguera García.

8. "Equipamiento para investigación en el ámbito de Big Data aplicado al área del Deporte y la Salud en el Instituto Mixto Universitario Deporte y Salud." Ref.: UNGR15-CE-3400. Entidad financiadora: Convocatoria 2015 de Ayudas a Infraestructuras y Equipamiento Científico-Técnico del Subprograma Estatal de Infraestructuras Científicas y Técnicas y Equipamiento (Plan Estatal de I+D+i) del Ministerio de Economía y Competitividad. Financiación: total 716,400.00 €, de los cuales corresponden 573,120 € son en modalidad subvención FEDER, y 143,280 € en modalidad préstamo para UGR. Fecha y duración: 2 años (24 meses), desde 1-enero-2016 hasta 31-diciembre-2017. IP: Víctor Manuel Soto Hermoso.

9. Proyecto AGUEDA- Active Gains in brain Using Exercise During Aging. Call I+D+i retos, Ref: RTI2018-095284-J100. Ministerio de economía y competitividad. IP: Esteban-Cornejo, University of Granada. 2019-2022. 210.000€.

10. Proyecto Backfit. Entidad financiadora: Instituto de Salud Carlos III, cofinanciado por la Fundación Europea. Fecha y duración: 2021-2024. IP: Víctor Segura Jiménez.

C.4. *Congresos*

Comunicaciones orales

1. *"Análisis de las diferencias cinemáticas entre el revés a una y dos manos de tenis mediante el uso de giróscopos."* XLI Congreso de la Sociedad Iberoamericana de Biomecánica y Biomateriales, Madrid 2018.
2. *"Análisis del golpeo de pádel remate por tres metros mediante el uso de giróscopos."* XLI Congreso de la Sociedad Iberoamericana de Biomecánica y Biomateriales, Madrid 2018.
3. *"Validación de wearables para el análisis técnico de tenistas."* XLI Congreso de la Sociedad Iberoamericana de Biomecánica y Biomateriales, Madrid 2018.
4. *"Influencia del calzado deportivo en la economía de carrera."* XLII Congreso de la Sociedad Iberoamericana de Biomecánica y Biomateriales, Madrid 2019.

5. ***"Validación del medidor de frecuencia cardiaca del nuevo polar Vantage M. Estudio Piloto."*** XLII Congreso de la Sociedad Iberoamericana de Biomecánica y Biomateriales, Madrid 2019.
6. *"Análisis de tres metodologías para la detección de asimetrías en aterrizajes de saltos."* I Congreso de investigadores del PTS, Granada, Marzo 2019.
7. *"Análisis biomecánico del remate de pádel plano en función del nivel de juego".* Investigación Didáctica y Estudios Curriculares Avanzados para la Educación y la Ciudadanía (CIIDEA), Palma, 2022.
8. *"Associantions of gait variability with inhibitory control in cognitive healthy older adults: the AGUEDA proyect."* 1st International Congress "Promoting Brain Health Through Exercise Across the Lifespan", Granada, 2021.
9. *"Associations between gait velocity parameters and brain amyloid-β levels in cognitive normal older adults: a cross-sectional analysis from the AGUEDA trial."* Alzheimer's Association International Conference (AAIC), Amsterdam, 2023.
10. *Is muscle strength associated with spatiotemporal gait parameters in patients with non-specific chronic low back pain? The Backfit Project,* (2023). Annals of the Rheumatic Diseases, *82*(1), http://dx.doi.org/10.1136/annrheumdis-2023-eular.6211

Posters

1. *"Step length variability and gray matter volume, and its derived association with executive function in cognitively normal older adults: The AGUEDA trial."* VIII Simposio EXERNET: "Ejercicio físico para la salud a lo largo de la vida", Almería, 2023.
2. *"EXOBOOT. Prototipo de exoesqueleto pasivo adaptado a la bota militar".* Ejército, Empresa y Conocimiento: Un alianza estratégica para el Horizonte 2035, Granada, 2019.
3. *"Análisis de la trayectoria de la raqueta de tenistas ATP en competición con un sistema fotogramétrico 3D lowcost".* XLI Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales (SIBB), Madrid, 2018.

C.5. *Responsabilidades institucionales, pertenencia a sociedades científicas*

- Desde 05/2018 – hasta la actualidad **Investigador a tiempo completo** en Grupo de Investigación CTS-545 (Human Lab), iMUDS. Funciones principales:

técnico de apoyo a la investigación y diseño y realización de artículos científicos.

- **Tutor profesional** en la entidad "Human Lab (iMUDS)-UGR" de estudiantes de Ciencias de la Actividad Física y Deporte en la asignatura "Prácticas externas" del curso académico 2018-19; 19-20, 20-21, 21-22, 22-23 y 23-24.

-Docente en el curso **"Diploma en enseñanza de Pádel (II ed.)"** años 2019, 2020, 2021 y 2022 en la asignatura "Biomecánica aplicada al Pádel."

-**Docente colaborador** en la asignatura optativa "Biomecánica aplicada" del cuarto curso de Ciencias de la Actividad Física y el Deporte de la Universidad de Granada.

-**Docente colaborador** en el Master de Investigación en Actividad Física y Deporte de la Universidad de Granada (itinerario de actividad física y salud).

-**Docente invitado** en la asignatura de Deportes de raqueta de la Universidad de Almería.

Parte D. OTROS MÉRITOS

D.1. *Capítulos de libro*

1. Coll, J. F. R., **Malagon, E. J. R**., Vecino, B. M., & García, G. D. (2023). Análisis de la cinemática y la variabilidad motora en remates de pádel en función del nivel de juego y de la intensidad de golpeo. *Viaje didáctico por el cuerpo y la mente: experiencia desde la abstracción científico-matemática a la educación física.* Dykinson S.L.

D.2. *Revisiones para revistas JCR*

- Frontiers in Physiology
- Perceptual and Motor Skills
- Mathematical Biosciences and Engineering

D.3. *Formaciones complementarias*

-Curso de iniciación a Matlab, Facultad de psicología, Universidad de Granada, 2019.

-Curso de iniciación a Blender, Universidad de Granada, 2019.

- Manejo y desarrollo de escáneres 3D fotogramétricos mediante ordenadores de placa reducida Raspberry PI, sincronización fotogramétrica y procesamiento de avatares (curso 20 horas).

-Manejo de MotionMetrix para análisis de la marcha y la carrera mediante captura de movimiento 3D sin marcadores (curso 25 horas).

-Experiencia en el manejo del sistema de captura de movimiento mediante cámaras de rango infrarrojo/visible y VR Optitrack y manejo del software Motive optical Motion Capture Software (curso 20 horas).

-Uso del sistema de obtención óptico de datos mediante barras transmisoras/receptoras trasladado al análisis de la caminata para la prevención y entrenamiento, Microgate- Optogait (curso 15 horas).

-Experto en análisis biomecánico de la marcha y postura con sistema baropodométrico software Freestep (curso 25 horas).

-Manejo de sistema de captura de movimiento SIMI Motion, grabación de movimiento mediante sincronización de cámaras de alta velocidad, procesamiento y tracking de movimiento 2D/3D, cálculo de variables posicionales y análisis (curso 30 horas).

-Experiencia en la utilización de analizadores de composición corporal mediante equipos de BIA y nefrología INBODY (curso 15 horas).