Departamento de Educación Física y Deportiva
Universidad de Granada
España

Curso de Doctorado:

"Nuevas Perspectivas en Investigación en Ciencias de la Actividad Física y del Deporte"

Walking speed modulation in young and elderly people

Doctorando:

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Editor: Editorial de la Universidad de Granada
Autor: Domenico Cherubini
D.L.: GR. 2829-2008
ISBN: 978-84-691-8355-7

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CERTIFICAN: Que el trabajo de investigación que se expone en la presente memoria de tesis doctoral “Walking speed modulation in young and elderly people”, ha sido realizado bajo nuestra dirección por D. Domenico Cherubini, y finalizada con todo aprovechamiento, así como revisada por sus directores que la encuentran conforme para ser presentada y defendida en su momento por el tribunal designado al respecto.

Y para que conste y en cumplimiento de las disposiciones vigentes, firmamos el presente certificado en Granada con fecha 18 de Septiembre de 2008.

Prof. Dr. Víctor Manuel Soto Hermoso   Prof. Dr. Aurelio Cappozzo

Domenico Cherubini: *Walking speed modulation in young and elderly people*

Abstract

Human locomotion is certainly the most analyzed motor task and subject of a great deal of literature. However, conclusions drawn are not always consistent and this is often caused by the variability of mean speed of progression (SoP), stride length (SL) and cadence (SF), which are not taken in due consideration. In addition, laboratory/experimental constraints impose values to these parameters that make walking non-spontaneous, possibly affecting the analysis. Moreover, secondary motor tasks influenced gait parameters and differences were observed when subjects walked at maximum speed compared to a comfortable pace.

The aim of this study was to verify the hypothesis that, in human walking, the increase in SoP will be supported by a pattern in the spatial-temporal parameters only whilst the effort is perceived as comfortable, and thus associated with the subjects capabilities.

The project was organized in two different steps with the following aims:

- In a first methodological study, the most appropriate parameters and analysis procedures were identified;
- In a second applied study, the parameters previously identified were used to answer to the purpose of the present work.

In the 1st methodological study, two groups of young (YG, n=25, 23±4 years) and elderly (EG, n=22, 71±4 years) health subjects participated in the study. They were asked to walk three times at “comfortable” (CS) and at “fastest” (FS) self-selected speed and two strides per trial were considered for the analysis. Stride duration (T) was recorded using a purposely built 4 m instrumented mat, and SF was computed as 1/T. A VICON 612® system was used to measure SL (AP displacement of a marker located over the C7 spinal process). Speed values (v) were computed as SL/T. Data were normalized with respect to subjects’ leg length. The relationships between normalized SL (λ), SF (φ) and v (ϖ) were assessed using bivariate regression analysis and Pearson’s product moment.

As hypothesised, the way the YG and the EG combine φ and λ to support SoP in the two different tasks performed was clearly different. A clear effect of φ and λ on speed of progression was found, but the correlation between the parameters was reduced with increasing speed. This fact suggests that young and elderly people coordinate with both φ and λ to sustain higher speed of progression, until this is within a range that they perceive as comfortable. Beyond this threshold, they can sustain the efforts picking up from their one’s capabilities, that differs from each other.

The utilized protocol, together with the data analysis procedures, has proved to be a useful tool for the aim of this research. In particular, the option to analyse the relationship between the temporal-spatial walking parameters separately for the two different specific walking tasks. But, although some interesting results were achieved, some questions were still open. In order to consolidate the results of the present study, the analysis of walking patterns in a space wider than that of a laboratory, and in more natural conditions, is desirable. Moreover, the application of an incremental walking speed protocol could be more effective to analyse the way people, differently aged, modulate the walking parameters to support variation in walking speed.

In the 2nd part of the study, any possible conditioning of the subject's natural gait was ruled out asking him or her to walk continuously along a circuit, in the centre of which a GAITRite® system was placed. Two groups of healthy elderly (EG, n.17, 67±4 years) and young (YG, n=28, 22±3 years) people volunteered for this study. They walked starting at their most comfortable speed, slightly increased speed of progression each 90 s, until they perceived the effort from hard to very hard. Then, they were asked to walk at the maximum speed. For each subject, the incremental test data was clustered in terms of the 33rd, 66th and 100th percentile of the Z-score speed values. This procedure allowed us to compare the data collected for the same exerted effort, even if the achieved speed could differ. The Pearson's correlation coefficient was computed with reference to the gait variables, for each speed condition, and for each subject. A linear hierarchical regression was conducted to highlight possible differences in the relationship between them, during the different walking efforts.

Both EG and YG supported the increase in SoP using SF more than SL, and the EG maintained the capability of exerting SF at a similar level as the YG. The SF and SL of both groups showed high correlation values with SoP only at the most comfortable speed. As speed of progression increased, these values tended to clearly decrease, differently progressing in the two sample groups. Above all, the linear hierarchical regression showed high significant differences of the regression models analyzed at each speed, in both EG and YG. Moreover, both EG and YG showed highly significant differences among the variances between - and within - subjects, for each parameter.

The results of the present study confirm our starting hypothesis. The way the subjects have to speed up pace depends on the subjective motor capability and on the required effort. It appears evident that the latter factor causes a wide inter-subject variability of the gait phenomenon described very frequently in the literature. The same variability that, when not considered, could lead to misleading conclusions as has been the case with several authors that dealt with, and tried to solve, the problem of human locomotion.

Keywords: Gait analysis, locomotion, stride parameters, gait strategies, elderly people.

Abstract en español

La locomoción humana es ciertamente la acción motora más analizada y argumento de una gran cantidad de bibliografía. No obstante, las conclusiones que han surgido no siempre coinciden, y esto, a menudo, se debe a la variabilidad de la velocidad de marcha, a la longitud (SL) y a la frecuencia (SF) de la zancada, factores que no son siempre adecuadamente considerados. Además, las restricciones tanto de los laboratorios como de los protocolos experimentales imponen valores a estos parámetros que hacen que la marcha no sea espontánea influenciando, probablemente, el análisis. Asimismo, gestos motores secundarios afectan los parámetros de la marcha, e incluso, se han podido observar diferencias cuando los sujetos han caminado a una velocidad máxima y cuando lo han hecho a una velocidad más confortable.

El objetivo de este estudio ha sido el de verificar la hipótesis de que en la marcha humana, el aumento de la velocidad determinado por un aumento de los parámetros espacio-temporales puede representar un patrón de la marcha que se manifiesta hasta que el esfuerzo es percibido como confortable, por lo tanto, relacionado a las capacidades del sujeto.

El proyecto ha sido organizado en dos partes con los siguientes objetivos:

- En un primer estudio metodológico han sido identificados los parámetros más adecuados y los procedimientos de análisis.
- En un segundo estudio aplicado, los parámetros precedentemente identificados han sido usados para responder al objetivo de este trabajo.

En el primer estudio metodológico han participado un grupo de jóvenes (YG, n=25, 23±4 años) y un grupo de ancianos (EG, n=22, 71±4 años) todos en buenas condiciones de salud. A ellos, se les ha pedido caminar libremente tres veces a una velocidad confortable (CS) y a una velocidad máxima (FS) y en función del análisis, fueron consideradas dos zancadas por cada prueba. La duración de la zancada (T) ha sido tomada utilizando un tapete instrumentalizado de 4 metros construido especialmente para tal fin, y la SF ha sido calculada como 1/T. Se ha usado un sistema VICON 612® para medir la SL (AP desplazamiento de un marcador colocado sobre la vértebra C7). Los valores de velocidad (v) han sido calculados como SL/T. Los datos han sido estandarizados por medio de la longitud de la pierna del sujeto. Las relaciones entre los valores normalizados de la SL (λ), la SF (φ) y de la v (ϖ) han sido evaluados utilizando un análisis de regresión bivariante y el coeficiente de correlación de Pearson.

Tal como se ha planteado en la hipótesis, el modo en el cual YG y EG combinan φ y λ para sostener la SoP en las prestaciones motoras ha sido claramente diferente en los dos grupos analizados. Un claro efecto de φ y λ sobre la velocidad de marcha ha sido hallado pero la correlación entre los parámetros se ha reducido al incrementar la velocidad. Este hecho sugiere que las personas jóvenes y aquellas ancianas coordinan tanto la longitud del paso como la frecuencia del paso para sostener una mayor velocidad de marcha, hasta que ésta se

encuentra en un rango que es percibido como confortable. Más allá de este límite, ellos pueden mantener el esfuerzo requerido usando sus propias capacidades individuales.

El protocolo que se ha utilizado -junto a los procedimientos de análisis de los datos- ha demostrado ser un instrumento útil para el objetivo de esta investigación, en particular, la opción de analizar las relaciones entre los parámetros espacio-temporales de la marcha separando los dos tipos de prestaciones. Si bien se han alcanzado algunos resultados interesantes permanecen abiertas algunas interrogantes. Para consolidar los datos del presente estudio, sería aconsejable realizar el análisis de los parámetros de marcha en un espacio más amplio que el de un laboratorio y en condiciones más naturales. Además la aplicación de un protocolo de velocidad incrementada de marcha podría ser más eficaz con el análisis de la manera como las personas de diversas edades regulan los parámetros de la marcha para soportar el incremento de la velocidad.

En la segunda parte del estudio, ha sido eliminado toda posibilidad de condicionamiento de la marcha natural del sujeto, pidiéndoles caminar continuamente a lo largo de un circuito, en cuyo centro fue colocado un sistema GAITRite®. Dos grupos, de ancianos (EG, n.17, 67±4 years) y jóvenes (YG, n=28, 22±3 years) saludables, han participado voluntariamente en este estudio. Han caminado partiendo a la velocidad más confortable para ellos, aumentando paulatinamente la velocidad de marcha, cada 90 s, hasta que percibían el esfuerzo entre duro y muy duro. Después, han realizado otra prueba a la máxima velocidad de marcha. Para cada sujeto, los datos del test de incremento de velocidad han sido reagrupados en relación al 33, 66 y 100 percentil del Z-score de la velocidad de marcha. Este procedimiento nos ha permitido comparar los datos recogidos en función del esfuerzo efectuado, por igual, por cada uno de los sujetos, independientemente de su velocidad de marcha. El coeficiente de correlación de Pearson, entre los parámetros de la marcha, ha sido calculado por cada grupo de velocidad y por cada sujeto. Una regresión jerárquica lineal ha sido efectuada para evidenciar posibles diferencias en las relaciones entre los parámetros durante las distintas fases de esfuerzo de la marcha.

Ambos grupos, el EG y el YG, han aumentado la SoP utilizando más la SF que la SL, y el EG ha alcanzado la capacidad de mantener una SF a un nivel similar al del YG. En ambos grupos, la SF y la SL ha mostrado valores de correlación muy altos con la SoP sólo a la velocidad más confortable. Con el aumento de la velocidad de marcha, estos valores tienden claramente a disminuir, procediendo de manera diferente en los dos grupos de sujetos. Sobre todo, en ambos grupos, EG y YG, la regresión jerárquica lineal ha mostrado diferencias bastante significativas entre los modelos de regresión calculados por cada rango de velocidad. Además, ambos grupos, EG y YG han mostrado, por cada parámetro de marcha, diferencias muy significativas entre las variantes inter-sujetos e intra-sujetos.

Los resultados del presente estudio confirman nuestra hipótesis de partida. La estrategia que los sujetos adoptan para aumentar la velocidad de marcha depende de las capacidades motoras de cada sujeto y del esfuerzo requerido. Se evidencia que este último factor causa una amplia variabilidad inter-sujetos del fenómeno de marcha, descrita muchas veces en la literatura especializada. La misma variabilidad que, si no es considerada, podría llevar a conclusiones engañosas, como en el caso de algunos autores que se han ocupado del tema, tratando de resolver el problema de la locomoción humana.

Palabras Clave: Análisis de la marcha, Locomoción, Parámetros de zancada, Estrategias de marcha, Mayores.

The last part of this thesis was the object of an oral presentation at the 13th Annual Congress of the ECSS (European College of Sport Science) held in Estoril (Portugal) the 9-12 july 2008; in proceeding, 490.

To my parents

ACKNOWLEDGEMENTS

This work was carried out in collaboration with the Laboratory “ErgoLab” of the Faculty of the Physical Activity and Sports Sciences of the Granada University (Spain), and the Locomotor Apparatus Bioengineering Laboratory of the Department of Human Movement and Sport Sciences of the University of Rome “Foro Italico” (Italy), during the years 2005 – 2008.

I express my sincere gratitude to my supervisor Professor Victor Manuel Soto Hermoso for his guidance as well as for his encouragement and confidence in me. In addition, he provided the necessary facilities for this study.

I am deeply grateful to my supervisor Professor Aurelio Cappozzo for his endless expertise and help in this work. I thank him for providing a sense of direction as I progressed in my career as a researcher. In addition to the never failing encouragement, he was always ready to answer my questions.

I was happy that Professor Philip Riches and Professor Ugo Della Croce, in view of their expertise in human movement biomechanics, were appointed as reviewers of this thesis. I thank them for their thorough attention on this study and their views, which have improved the manuscript.

I wish to express special thanks to the entire staff of the two Laboratories involved in this study. In particular, Claudia Mazzà and Fabrizio Pecoraro PhDs of the Locomotor Apparatus Bioengineering Laboratory of Rome for interesting discussions and expertise in the field of stereophotogrammetry and human walking, and Virginia Aparicio and José María Heredia of the “ErgoLab” for their invaluable assistance during the test sessions.

I wish to thank Professor Arnaldo Zelli for his expert statistical assistance, guidance and collaboration.

I thank Mounir Zok, PhD, and particularly my nieces, Giulia e Francesca Di Mattia, who looked closely at the final version of the thesis for English style and grammar, correcting both and offering suggestions for improvement; while, for the Spanish style and grammar in the summary, I wish to thank Alina Tufani.

I am grateful to all my co-workers and friends for their supportive interest and encouragement during these years.

I wish to thank particularly also Pablo Fernández and his family. His parents, Jesús Fernández and Rosario Galvez, and his brothers, Jesús and Rocío, for their deep friendship and their precious help during these years. They actually were my second family in Spain.

I owe my special thanks to all subjects who participated this study.

Finally, I wish to express my dearest thanks to my parents for their support and encouragement. My deepest and warmest thanks go to my mother whose love and support has kept me going, and to my father, who shared with me only the beginning of this long route but, I am sure, as he always did, is doing too now, from where he is. To them I dedicate this thesis.

This study was financially supported by the Department of Human Movement and Sport Sciences of the IUSM of Rome, Italy.

Rome, Sep. 2008

Domenico Cherubini

Terms' glossary:

SoP	Speed of progression
SL	Stride Length
SF	Stride Frequency
YG	Young Group
EG	Elderly Group
CS	Comfortable Speed
FS	Fastest Speed
Cad	Cadence
Vel	Velocity
v	Speed values
λ	Normalized Stride Length
φ	Normalized Stride Frequency
ϖ	Normalized speed values

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1. INTRODUCTION AND OBJECTIVE OF THE STUDY

1. INTRODUCTION AND OBJECTIVE OF THE STUDY

Human locomotion is the most important activity of daily living and certainly the most analyzed movement in the laboratories of human movement. For this reason, it is the subject of a great deal of literature. In particular, information obtained by looking at stride length (SL) and stride frequency (SF) has been used in the literature to describe human locomotion, in order to distinguish between normal and pathological gait, and to compare different populations. However, the conclusions are not always consistent; for instance, Danion et al. (2003) observed that changes in walking speed are due more to a change in SL than in SF; while Larish et al. (1988) noticed that older subjects tend to increase their SF to speed up their gait. On the contrary, Brenière (2003) highlighted that subjects combine these two parameters equally. This discrepancy, is often caused by the fact that variability of the motion pattern with respect to the mean speed of progression, stride length and stride frequency is not taken in due consideration, even if recently the variability of these parameters was specifically observed (Jordan et al. 2007; Owings et al. 2004*). In addition, laboratory/experimental constraints impose values to these parameters that make walking non-spontaneous, possibly affecting the analyzed parameters (walking on a treadmill; observe some parameters in order to infer other aspects that are not directly observable; walking through a previously established way).

Moreover, in some studies, data were analysed not accounting for the fact that subjects could change their way to modulate stride frequency and stride length depending on the instructions they were given, while Shkuratova (2004) highlighted that balance strategies during gait are task specific and vary according to age. This could be especially true if subjects were asked to reach their maximum capacity.

In a previous study (Cherubini et al. 2005), some differences were found in the modulation of spatial-temporal parameters of gait, adopted by the subjects, when they were asked to reach their maximum speed compared to a most comfortable pace, and between elderly and young subjects when asked to support variations in walking speed. These aspects allowed us to hypothesize that, during walking, the increase in speed of progression will be supported by a pattern in the spatial-temporal parameters only whilst the effort is perceived as comfortable, or in other words, an effort that could be easily exerted by each subject without any resort to energy supplies, or without any sense of fatigue, and thus be associated with the subjects capability.

The aim of this investigation was to check this hypothesis for young and elderly people.

The project was organized in two different steps with the following aims:

- In a first methodological study, the most useful parameters and analysis procedures were identified;
- In a second applied study, the previously identified parameters were used to respond to the purpose of the present work.

2. BACKGROUND

2. BACKGROUND

2.1 Historical references

The human and animal movement aroused, through the centuries, a great interest to some great historical figures, whom empirically wrote and drew about it. Aristotle (384-322 B.C.), who coped with this topic in philosophical terms, wrote about "de Incessu Animalium"; while Galen (131-201), as gladiator’s doctor, was probably the first example of sports medical doctor, and he applied his experiences to the knowledge of the human body and movement; later Leonardo da Vinci (1452-1519) was interested to animal and human movements trying to analyse them according to the laws of mechanics, leaving us many drawing and writing about this (Figure 2.1.1.); in the 17th century Francesco Antonio Alfonso Borelli (1608-1679), Neapolitan physiologist and physicist, who was Galileo disciple, wrote the “De Motu Animalium” in which he related muscular movement to mechanical principles.

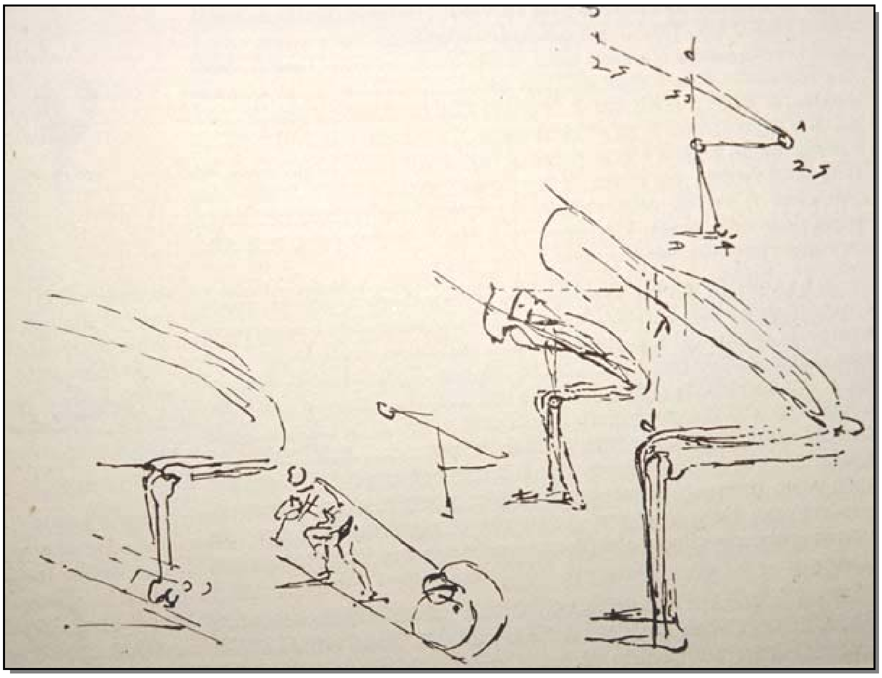

Figure 2.1.1. Drowing by Leonardo da Vinci, from the Atlantic Code, end of 1400)

He was the first to explain muscular movement and other body functions according to the laws of statics and dynamics. The work was published posthumously in two parts by his colleagues (Figure 2.1.2.).

Figure 2.1.2. J. A. Borelli, de Motu Animalium, cover and Table IV showing his biomechanical analysis of a man bearing a load whilst standing on the toes of one foot; 1710.

However, human locomotion and gait cycle were described in a more objective and quantitative manner starting from the second half of the nineteenth century, when the first analysis based on quantitative experimental observations were developed due to the availability of the new photographic techniques, thus allowing for the investigation of different locomotion parameters. This investigation process started with the work of Eadweard Muybridge (1830-1904) who developed photographic serial pictures in order to represent animal and human movements (Figure 2.1.3.). At the same time Etienne Jules Marey (1830-1904) used graphic and photographic procedures to describe movements, and he gave an outstanding contribution to the development of instruments to detect kinematic and dynamic quantities (Figure 2.1.4.).

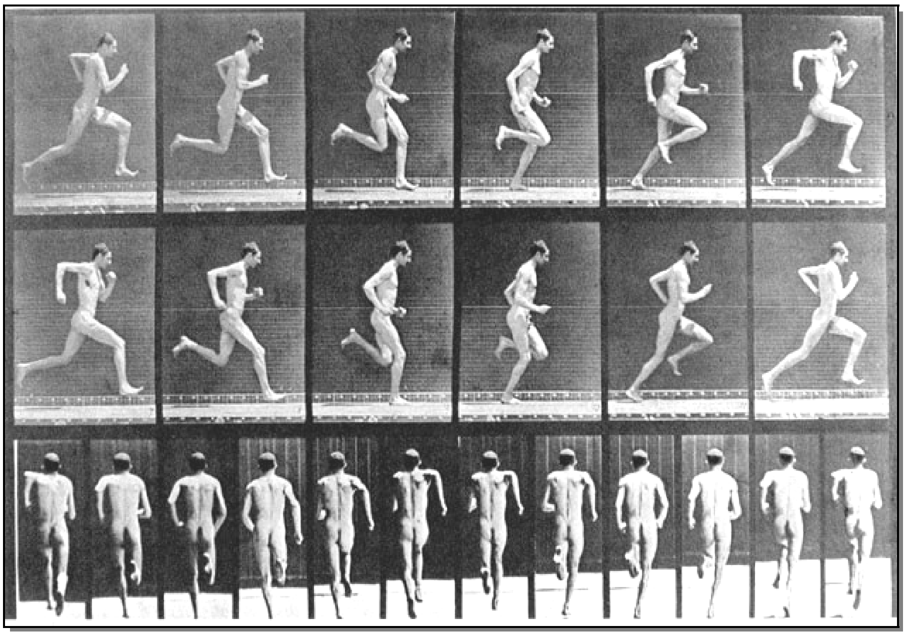

Figure 2.1.3. E. Muybridge: Photographic sequence of a running man.

Figure 2.1.4. Man in action carrying a device to record pressure vs. ground and vertical movement of the head. (Marey, E.J., La Machine Animal, Felix Alcan, Paris, 1886)

However, the acknowledgement of the authorship of the modern mathematical approach to the human movement study goes to Wilhelm Braune e Otto Fischer. Their accurate mathematical analysis (Figure 2.1.5.) conducted on the experimental data obtained "dressing" a subject with thin illuminated tubes, allowed the computation of the three-dimensional pose of the body segments during walking.

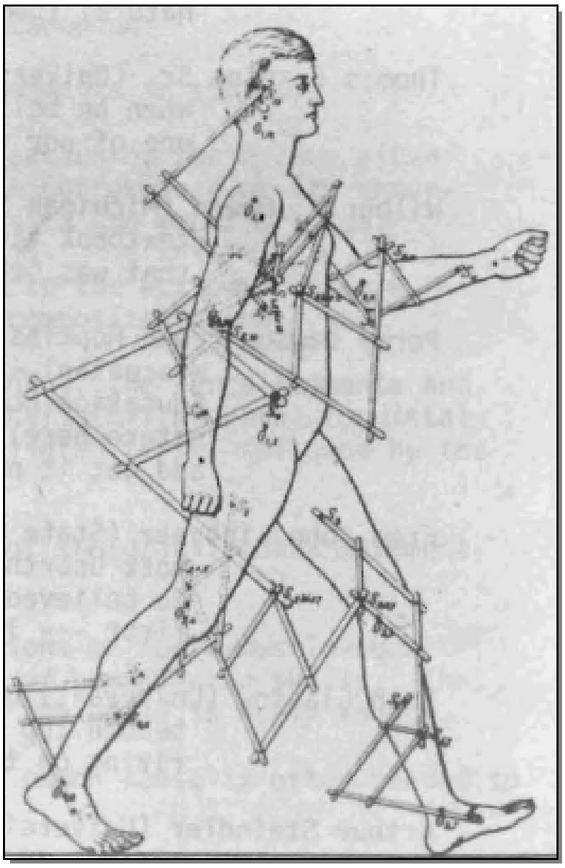

Figure 2.1.5. Model of the human by which the body's centers of gravity may be determined. (From Fischer, 0 Der Gang des Menschen II. Teil, Teubner, Leipzig Tag I.)

At the beginning of the 20th century, from the "Russian School", stood out Nikolaj Bernstein (1896-1966) who was involved in many investigation fields, among which the studies about the inertial parameters of body segments and body kinetics have to be underlined. Moreover, in 1947, the National Council of the U.S. on Artificial Limbs, Veterans Administration and Surgeon General of U.S. Army commissioned the College of Engineering of the Berkeley University to study the prosthesis problem for amputated soldiers from the second world war. It was the birth of the “Californian School”, in which Inmann produced basic results about the movements of the body segments during locomotion. In addition, the concurrent development of new advanced technology contributed towards the improvement of the biomechanics knowledge. Cunningham and Brown (1952) were the designer of the first six component force plate, an instrument able to measure the forces exchanged between the ground and the subject. In the meantime, the instrumentation for electromyography was also developed. The first reported kinesiological studies that used electromyography were those of Inman et al. (1944) and of the University of California (1947).

The modern gait analysis laboratory was thus established at the end of the Second World War, when there were a large number of limbless ex-servicemen, and the Government of the United States of America realised that a major effort was needed to develop improved prostheses, particularly lower-limb prostheses, to get these people walk again. As part of this large research project, the University of Calfornia at Berkely was requested to perform comprehensive studies on normal and disordered locomotion. Much of our present understanding of the biomechanical mechanisms used in walking and running came out of this research. Since then, many papers have been published concerning the mechanics of walking, both for healthy and pathological subjects.

2.2 Human locomotion

Terrestrial human locomotion is a phenomenon that can be simply described as the displacement of the whole body from one point to another in space, normally by means of a bipedal cyclical gait (Saunders et al. 1953).

A gait cycle is the interval of time that starts with the heel-strike of one limb, e.g. the right, and ends at the following heel strike of the same limb. Looking at one limb at a time, the whole cycle can be divided in two phases. The first starts with a heel-strike and ends when the toe of the same foot leaves the ground, and it is called the "stance phase". In the next phase, called "swing phase", the limb has lost contact with the ground and is being swung forward until the heel strikes the ground once again (Figure 2.2.1.).

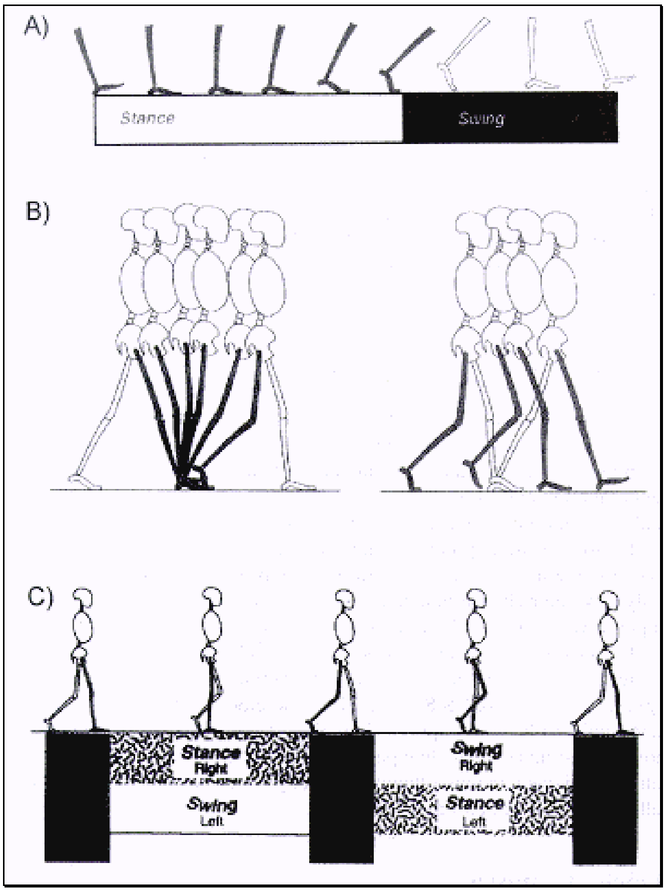

Figure 2.2.1. Walking gate phases. (From Grasso et al. in: http://www.hsantalucia.it/quaderni/quaderno13.htm)

During locomotion, the right and the left limb alternate out of phase with each other.

Human locomotion is characterised by two principal gait: walking and running. During walking the body never loses contact with the ground, that is at least one foot is on the ground at all times. During running each phase of single foot contact is followed by a phase in which both feet are simultaneously off the ground. This makes it possible to move either at a slow speed for long periods of time or at over 10 $m \cdot s^{-1}$ during a sprint (Saibene et al. 2003).

The present study deals with the most common and basic of these two locomotor acts, i.e. walking.

Walking is learned during the first year of life and a mature gait pattern is reached by an individual around the age of seven and maintained until the age of sixty (Winter 1991). This motor act requires the efficiency of many structures and functions of the human body. In particular, controls at different levels are required: support and postural control and adaptation of the body to unexpected changes in the environment (Spirduso 1995). Vision is used to monitor the direction and speed of movement (Grasso et al.1998), the vestibular system helps to maintain equilibrium by providing information about both head orientation acceleration. Proprioceptive information from muscles, joints, and skin is used to determine muscular forces produced and joint angles. During walking, the vertical line passing through the centre of mass transfers from one foot to the other in a series of successive losses of balance. Thus, in the act of walking, the mechanical equilibrium of the body is continuously perturbed and recovered by forming new bases of support through the alternate forward movement of the legs.

Usually, speaking about locomotion, we refer to the lower limb movements that initiate and sustain locomotion (Inman 1981; Winter 1991; Winter et al. 1993), but the trunk-head coordination holds a role that seems to be significant during gait though it is not clear till now. Winter et al. (1993) modelled the upper body as a simple pendulum and concluded that the vestibular system plays a minimal role in maintaining posture and balance during walking. In contrast, it has been suggested that the motion pattern of the upper part of the body is important for reducing energy consumption (Cappozzo et al. 1978) and maintaining balance (Pozzo et al. 1990). This has produced, in recent years, an increased focus of attention for the intersegmental coordination between rhythmic leg, pelvis, trunk, arm and head movements, in the study of gait. The spinal segments demonstrated complementary movements to the motion of pelvis, in particular with respect to flexion/extension and lateral flexion (Crosbie et al. 1997). The pelvic motion responds to the needs of the subjects to advance the lower limb and to transfer the body weight from one supporting side to the other during normal locomotion. In the sagittal plane, the head motion is coordinated with respect to the motion of the trunk (Pozzo et al. 1991). Therefore, as the trunk moved downward at heel contact, the head rotated backward to compensate for trunk motion (Cromwell 2003). These body segments move, with respect to the pelvis, in a coordinate fashion, so that their total energy variation during the walking cycle has a lower magnitude than it would have if trunk and head moved rigidly with the pelvis.

Moreover, head-trunk coordination helps to organize the inputs from the visual, vestibular and somatosensory systems to maintain equilibrium while performing various static or dynamic motor tasks including walking (Bril et al. 1998). The head is intermittently stabilized, and the angle of this stabilization depends from the performed motor task, is related to an ocular fixation point in the direction of gaze in space, and it is probably regulated on the basis of a predictive mode of sensory motor control (Pozzo et al. 1989). The vestibular system plays an important role in stabilizing the head, during locomotion, by means of angular vestibulocollic, linear vestibulocollic and cervicocollic reflexes, which act to move the head in the compensatory direction as trunk movements (Hirasaki et al. 1999).

In some studies, a significant effect of walking velocity on body segments kinematics were found too (Hirasaki et al. 1999; Hanlon et al. 2006). For instance, as walking velocity increased, pelvis-torax coordination changed from almost in-phase towards antiphase, without ever actually reaching this pattern. By means of a spectral analysis of horizontal pelvic and thoracic rotations during treadmill walking (Lamoth et al. 2002), it was observed that, as walking velocity increased, a triphasic component emerged in the pelvic rotation, while thoracic rotations remained harmonic across all walking velocities. Moreover, it has been reported that human walking with the speed range of 1.23-1.25 m/s is most efficient from the energy consumption perspective (Waters et al. 1999). While increasing walking speed leads to increased muscle activity in the lower extremities and changes in the temporal and distance characteristics of gait (Chiu et al. 2007). Further, the study on the effect of walking speed on heel strike initiated shock waves indicated that increasing walking speed tends to contribute more dynamic loading to the musculoskeletal system (Voloshin 2000). Also the vertical and horizontal ground reaction forces tend to be affected by walking speed, especially in the loading response and mid-stance phases (White et al. 1996). But variation in locomotion speed as a consequence of variation of the walking environment was also observed. Indeed, a reduction of the locomotion speed has been already described in adults walking in an unfamiliar way or encountering locomotor difficulty, especially without vision (Assaiante et al. 1989; Nadeau et al. 2003).

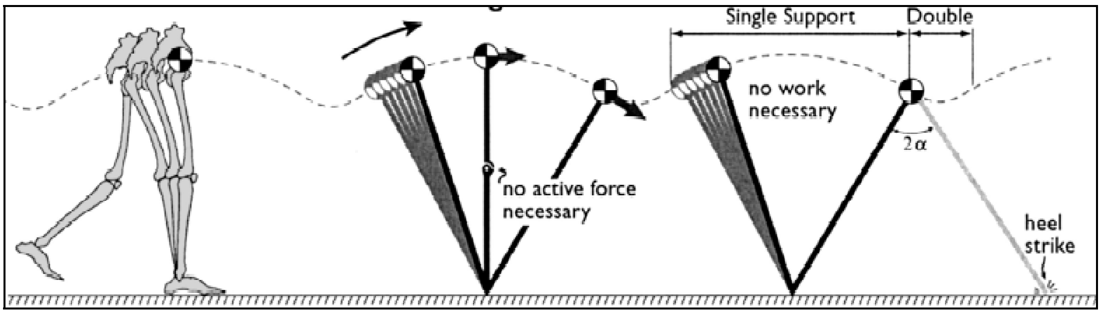

Figure 2.2.2. Schematic diagram of the simple inverted pendulum model of walking, which requires energy not for pendular motion but rather to redirect the body's center of mass (COM) between steps. During single support (when one leg contacts the ground), the rigid pendulum conserves mechanical energy, and the COM can be supported with no muscle force (From Kuo et al. 2005).

Although legged locomotion is the result of the coordinated action of dozens of muscles, many of them being bi-articular, exerting force via tendons and producing the movement of a multitude of bones and body segments, each gait can be described by a simple paradigm which helps to understand the overall mechanics of the progression along the ground. Classically, it has been described by an inverted pendulum/rolling egg paradigm (Margaria 1976). In those models (Figure 2.2.2.) the potential energy and the kinetic energy continuously exchange, resulting in a total mechanical energy with a smaller change over the stride with respect to the two components taken separately (Saibene et al. 2003).

However, a recent simulation analysis using a multi-segmental musculoskeletal model found that considerable muscle work is needed to produce the inverted pendulum-like motion (Neptune et al. 2004). Elastic energy utilization that stores and returns mechanical energy is considered to be an important metabolic energy saving mechanism (Alexander 1988). Gravitational potential and kinetic energy have the potential to be stored as elastic energy in compliant connective tissue and tendinous structures, and subsequently released to do positive work at a later point in the gait cycle, so reducing the necessary muscle fiber work (Sasaki et al. 2006). The subjects differ in their ability to minimize energy oscillations of their body segments and to transfer mechanical energy between the trunk and the limbs. This differentiation between subjects produces the variability that all organisms exhibit across a wide range of perceptive and motor functions (Van Emmerik et al. 2002) and that was the subject of many studies about human locomotion. Mainly, variability of step kinematics was observed both in young and elderly people. For instance, the relationship between age and step width variability was observed, underlining that the step width variability of older adults was significantly larger than that of young adults (Owings et al. 2004); stride variability was shown to be modulated by stride frequency and stride length (Danion et al. 2003); while stride length and stride frequency play an important role in determining stride variability, aging and pathology may exert an overriding effect on stride variability (Gabell et al. 1984; Hausdorff 2005; Grabiner et al. 2001). Moreover, Li (2005) found that variability in gait appeared to have a structured nature, that suggests that variability could be functional and not just random variations interfering with normal functioning, as in Hausdorff (1997; 1999).

As we observed above, there are so many features that influence walking. But, within the complex motor pattern that characterizes a walking cycle and that appears so variable to the observer in many of its details, the aspects that are typical of the locomotor act can be separated from those that are peculiar to a particular individual or to the contingent characteristics of the environment. Indeed, individual characteristics of the mechanical energy expenditure were correlated with the corresponding kinematic characteristics (Bianchi et al. 1998), so that the relevant pattern results in an individual trait.

2.3 Ageing effects

Locomotion in general and walking in particular, together with postural stability, are fundamental motor tasks for daily living, influencing people's self-sufficiency, both at individual and at social level. For this reason, the maintenance of locomotion ability is fundamental as age progresses. Ageing is a natural process leading to gradual and progressive deterioration of the living organism functions.

As indicated by physiological and performance measures, functional capacity generally improve rapidly during childhood and reach a maximum between the late teens and thirty years of age. Functional capacity then declines with age, and its deterioration is influenced by lifestyle characteristics (Jackson et al., 1995). However, not all functions decline at the same rate (McArdle et al., 1996), and are greatly influenced by regular exercise (Figure 2.3.1.).

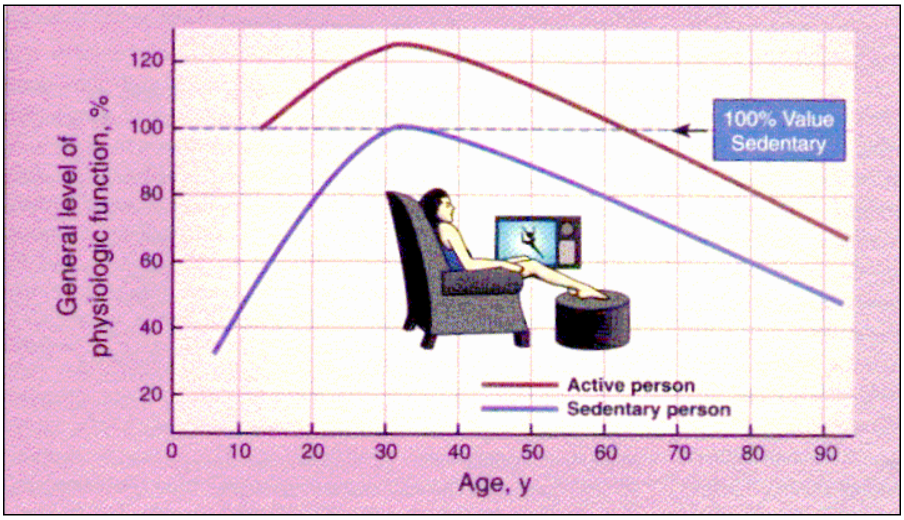

Figure 2.3.1. Changes in physiologic function with age: a comparison between active and sedentary people (from McArdle et al. 1996)

With the above mentioned decrease of the functional capacity, the elderly walking performance starts to decline with a gradual decrease of walking speed (Bendall et al. 1989; Shkuratova et al. 2004). In normal aging, walking speed decreases both at self-selected (Himann et al. 1988) and maximal (Ekdahl et al. 1989) speed. A significant association between increased postural sway and decreased walking speed has also been found (Lord et al. 1996*). For older people, control of dynamic balance can become increasingly difficult (Winter et al. 1990), and lead to an increased risk of fall during walking (Tinetti et al. 1988).

Two categories for causes of falls (Craik 1989) can be distinguished: the stimulus that results in the loss of balance, and the inability of the older persons to correct for the unexpected loss of balance. Several factors influence both categories, such as the status of the skeleton, neuromuscular (Burnfield et al. 2000; Kerrigan et al. 2001), visual, and cardiovascular systems (Puggaard et al. 2000), cognition, the use of medication, and environmental factors (Tinetti et al. 1995; Koski et al. 1998). The elderly are prone to a variety of diseases that affect these systems, including cataracts, glaucoma, diabetic retinopathy, and macular degeneration, which all affect vision; diabetic peripheral neuropathy, which affects position sense in the feet and legs; and vestibular system degeneration. Neuromuscular pathologies resulting in abnormal gait patterns are a major cause of falls. Those pathologies are frequently combined with arthritis resulting in restricted movements which increase the risk of falling. Several gait parameters have been found to be abnormal in elderly people with a history of falls compared with non fallers (Hausdorff et al. 1997; Wolfson et al. 1990). As mentioned above, most of the cross-sectional studies show that with ageing there is a slowing in sway, gait patterns have a wider base, there is an increased time in double leg support phase of walking as well as a decrease in stride length (Figure 2.3.2.), a decrease in trunk rotation and an increase in pain and discomfort that, in turn limit movement (Patla 1994). Sedentary older adults are also known to adopt a more cautious walking style with shorter step lengths and slower step velocities than active older adults (Rosengren 1998).

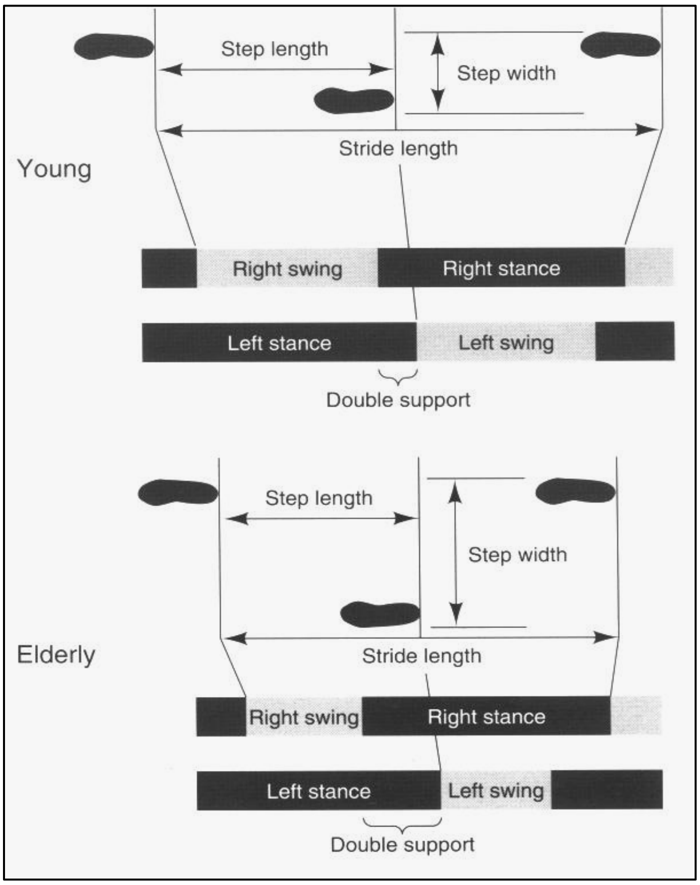

Figure 2.3.2. From "Biomechanics of human gait" by E.Y.S. Chao. In *Frontiers in Biomechanics (p. 226)* by G.W. Schmid-Schonbein, S.L. Y. Woo, and B.W. Zweifach (Eds), New York: Springer-Verlag 1986.

Elderly individuals for whom the "physiological" ageing process mentioned above does not imply invalidating disturbances or abnormalities of the neuro-musculo-skeletal system, and who do not suffer from other forms of disability and/or pathology, can be defined as "healthy". In Italy and in many other countries, healthy elderly represent over 20% of the population. These elderly, although healthy in the aforementioned sense, are at risk of disablement. Indeed, some studies examining the functional status of non-institutionalised persons over 65 highlighted that many people had difficulties in bathing, or in walking, and in bed or chair transfers. The rate of difficulty increased progressively over 65, climbing sharply in the 80-ies (Leon et al. 1990, through Schultz 1995).

All over the world, elderly people represent a growing segment of population, hence it is of great importance to improve knowledge about the elderly in general and about his/her gait pattern in particular.

2.4 Spatial and temporal parameters of human locomotion

As mentioned above, during locomotion, right and left limb alternate out of phase with each other, in the “stance phase” and in the “swing phase”, which are determined by the feet contacts. Observing the gait cycle in spatial and temporal dimension, many different parameters have been used in the literature to describe human locomotion, to distinguish normal and pathological gait, and to compare different populations (Brand et al.1981; Cappozzo 1983; Zijlstra et al. 2003).

The measure of the distance between subsequent feet contacts allows for the definition of the following gait parameters (Figure 2.4.1.):

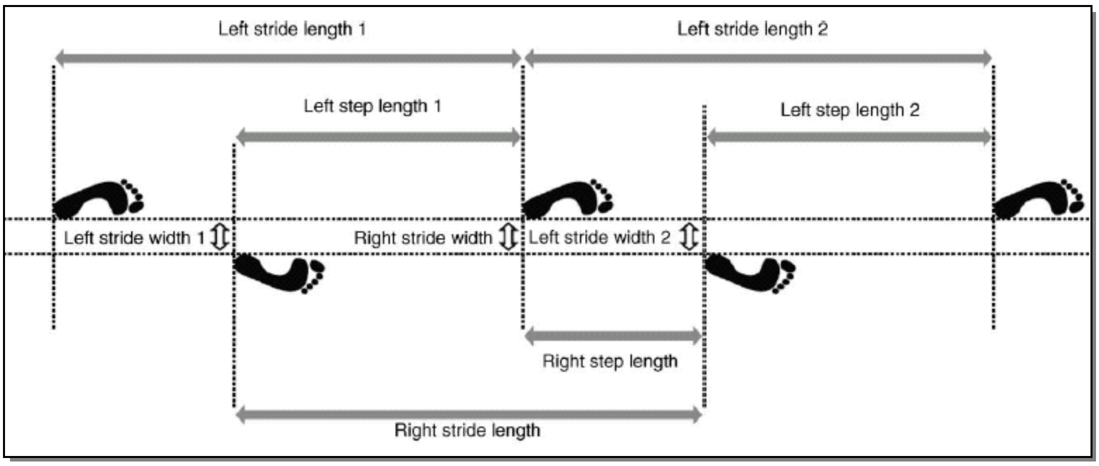

Figure 2.4.1. Spatial parameters of walking. From Huxham et al 2006.

- Stride length: the distance between two successive steps. Values of about 1.15 m have been reported in the literature for normal adults walking at self selected speed (Lord et al. 1996)**.

- Step length: the distance (measured in the sagittal plane) between one foot strike and the next (left to right or right to left). Its value is half of the stride length for healthy adults.
- Step width: is the distance (measured in the frontal plane) between one foot strike and the next (left to right or right to left). Values for normal adults are about 0.10 m (Owings et al. 2004).

The measure of the time intervening between subsequent feet contacts allows to define the following gait parameters (Figure 2.4.2.):

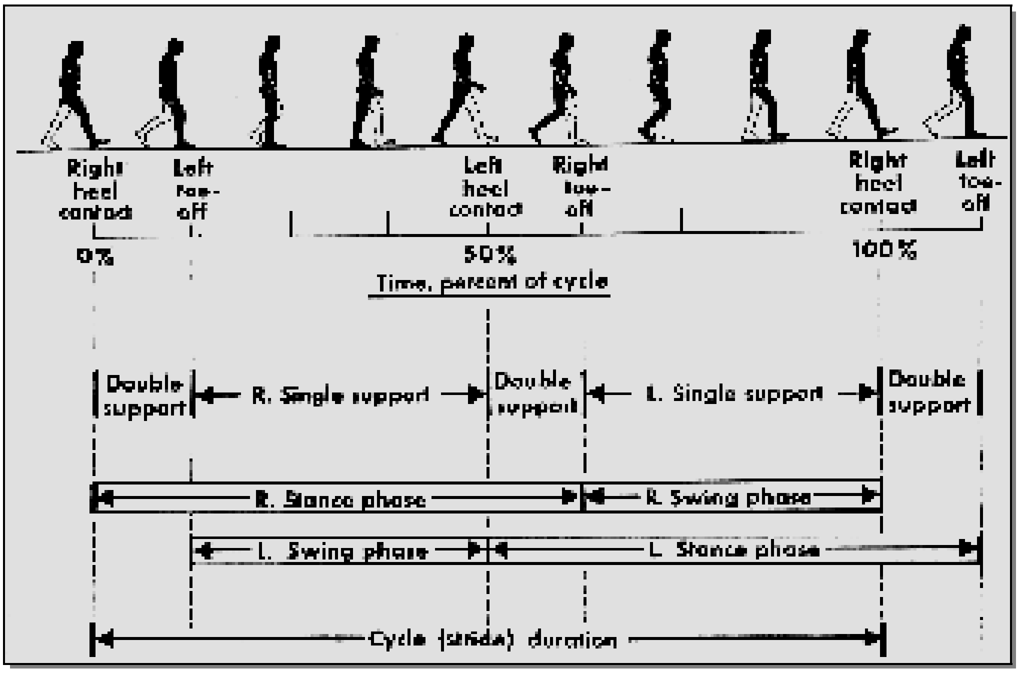

Figure 2.4.2. Time dimensions of the walking cycle (Inman et al. 1981)

- Stance phase duration: the interval of time during which one of the feet is in contact with the ground (64% of gait cycle in normal adult walking, Lord et al. 1996)**.
- Swing phase duration: the interval of time during which one of the feet is off the ground (34.5% of gait cycle in normal adult walking, Winter et al. 1990).

- Double support phase duration: the interval of time when both feet are on the ground (31% of gait cycle in normal walking, Winter et al. 1990).
- Cadence: the number of steps (left and right) taken per minute (about 110 st/min for normal adults, Winter et al. 1990).
- Mean speed of progression: the distance moved in the time unit (about 1.10 m/s in normal adults, Lord et al. 1996).

Relatively unsophisticated instruments can be used to measure these parameters; Sekiya et al. (1997) proposed the use of a long piece of paper with ink-satured material attached to the toe and heel of the subjects' shoes.

This methodology could be easily used in field research. Otherwise, in the laboratory, the identification of subsequent stride or step cycles requires higher accuracy and it is performed with more costly equipment. Some examples are conducting foot switches (Zijstra et al. 1995), pressure-sensitive foot switches (Nilsson et al. 1987; Nevill et al. 1995), ground reaction forces (Verkerke et al. 1998). Recently, some studies have reported gait analysis based upon the use of accelerometers placed on trunk, thigh, shank or foot (Moe-Nilssen 1998; Zijstra et al. 2003), that seems to be a suitable method to use in settings not restricted to a laboratory (Moe-Nilssen et al. 2004; Zijstra et al. 2003).

Many studies have examined spatial and temporal parameters to describe the gait of elderly people and highlight the differences with respect to younger subject.

The gait pattern of subjects older than 65 years is characterised by shorter and broader strides, more limited ankle movement, lower swing-to-stance time ratios, and hence increased period of double support (Ferrandez et al. 1988; Hageman et al. 1986; Winter et al. 1990; Kressig et al. 2004). Age differences in gait pattern, however, can be attributed almost solely to the slower gait of older people. When the gait patterns of young and elderly subject have been compared under similar walking speeds, the differences were found to be minimal (Ferrandez et al. 1990; Spirduso 1995). Both young and elderly subject manipulate stride length, swing phase duration, and stride frequency to voluntarily slow or speed up their gait (Brenière 2003). However, older subjects tend to increase their stride frequency (Larish et al. 1988). Increasing stride length also decreases the amount of double-support time, hence forcing the subject to implement a gait pattern that requires a greater balance control ability. At enforced very slow walking speed, older subjects tend to prolong the double-support phase of the gait cycle in order to enhance their balance (Gillis et al. 1986). Overall, during slow walking, very old healthy individuals and younger subjects exhibited similar stride parameters, while during fast walking the former population used shorter and more frequent strides than the latter population (Shkuratova et al. 2004). There are several explanations for the preferred slow gait of older people. Endurance of weaker muscles in the lower limbs is maximised with the use of shorter strides, and the energy cost of walking is minimised (Larish et al. 1988), even if Bertram (2005), by forcing to use constrained speeds, stride frequency and stride length, observed that the control of human walking is influenced by factors other than global cost of travel. Less flexible ankle and knee joints constrain the stride length. Having a more precarious balance on one foot encourages individuals to spend less time in the single-support phase of gait. Except for unexpected perturbation of balance, a slower gait also allows an older person more time to monitor the progress and result of walking and to react to changes in the environment (Spirduso 1995).

Others authors, underlined that changes in the gait patterns associated with aging are minimal in healthy individuals who do not have physical impairments; conversely, such changes can be related to health status (Engle 1986), physical inactivity (Larish et al. 1988), or pathological condition (Imms et al. 1981).

The variability of the spatial and temporal gait parameters has also been investigated. Step kinematic variability, as measured by the standard deviation, has prospectively predicted falls in older adults (Maki 1997; Hausdorff et al. 2001). Concurrently collected spatial and temporal step kinematics revealed that step length variability and step width variability had greater predictive power for falls than step time variability (Maki, 1997). Moreover, within the step kinematic variability, the step width variability seems to be the more meaningful descriptor of locomotion control of older and young adults, than step length and step time variability (Owings et al. 2004). Even though the spatial and temporal variability of the stride relate to each other, stride length and stride frequency, have distinct effects on gait variability and both determined the variability of human gait (Danion et al. 2003). However, in recent studies the need for a sufficient number of steps to compute step kinematics variability has been noted (Bauby et al. 2000; Grabiner et al. 2001). A minimum of 400 consecutive steps were reported as required to calculate a stable measure of step kinematics variability during treadmill walking (Owings et al. 2003).

Gait parameters can be then usefully utilized to assess impairments in balance control, functional ability, and risk of falling in both young and elderly subjects.

3. THE METHODOLOGICAL STUDY

3. THE METHODOLOGICAL STUDY

3.1. Methods

3.1.1. Subjects

The stride parameters during walking was analysed in two groups made of healthy elderly and young subjects, respectively. The first group was composed by twenty-two females, while the second one was composed by eight male and seventeen female. The volunteer subjects signed an informed written consent before participating in the study.

Their ages, heights and body mass data are shown in table 3.1.

Table 3.1. Descriptive analysis of the subjects participating in the study

	Elderly group (22)				Young group (25)			
	Age (years)	Height (m)	Leg Length (m)	Body mass (kg)	Age (years)	Height (m)	Leg Length (m)	Body mass (kg)
Mean	71.4	1.5	0.88	64.9	23.6	1.7	0.93	62.0
SD	3.9	0.1	0.04	8.0	4.2	0.1	0.05	11.4

Each subject was submitted to a medical examination certificating the health status; only those having no history of vestibular disease or other disorders that would affect their normal locomotor performance were selected.

3.1.2. The stereophotogrammetric system

To determine the stride length from the Antero-Posterior displacement of the subject's body, a 9 camera VICON 612® stereophotogrammetric system was used, as available in the biomechanics laboratory of the Department of

Human Movement and Sport Sciences at the University of Rome “Foro Italico” (Figure 3.1.2.1.).

Figure 3.1.2.1. The biomechanics laboratory of the Department of Human Movement and Sport Sciences at the University of Rome “Foro Italico”

The system allows a computer reconstruction of the instantaneous position in the 3D space of markers applied on the surface of the subject’s body. The system has an accuracy in identifying marker location within 2mm, as assessed performing the spot-check described in Della Croce and Cappozzo (2000).

Cameras were located in the laboratory so that the relevant measurement volume was 6x2x2 m^3. Marker positions were captured at a frequency of 120 samples per second. Prior to data collection, the stereophotogrammetric system was calibrated using a dynamical calibration approach.

One spherical retro reflecting marker (14 mm in diameter) was positioned on the subjects’ skin over the spinous process of the seventh cervical vertebra

(C7). In this respect, as in the Saunders' definition, the human walking is the displacement from one point to another in space of the whole body; the latter was considered as a rigid body. In this sense, the stride length is the distance covered by the subject's body between two successive steps, and then, knowing the exact time of the heel strike, any point of the body could be useful to determine the stride length. The C7 was chosen because it is easier to identify by each camera at each time, without any problem of losing the marker due to the impact with the ground. Two markers were positioned on an elastic band that the subjects wore on their heads so that it covered their foreheads. These markers were made to define an antero-posterior axis that allows us to determine the stride length with respect to this axis and not with respect to the external space. This is to avoid the problem of a non-aligned walking with the antero-posterior axis of the laboratory that could determine an under-measured stride length.

3.1.3. The instrumented mat

Foot-ground contact was detected using a 4 m long instrumented mat, also available in the Biomechanics laboratory of the IUSM of Rome. This was laid on the floor so that at least two strides could be recorded.

On the pathway on which the subjects walked, adhesive copper strips (foil) seven millimetres wide were laid longitudinally with a space of 3 mm between them. These strips were wired to two independent circuits, one for each foot, in such a way that when a subject's foot, wearing a sock made of a conductive fencing textile, comes in contact with the ground, two adjacent strips are short-circuited and a signal is generated (figure 3.1.3.1.). This signal was fed to the A/D converter of the VICON® system. This connection allowed for the synchronisation between the mat and the stereophotogrammetric data.

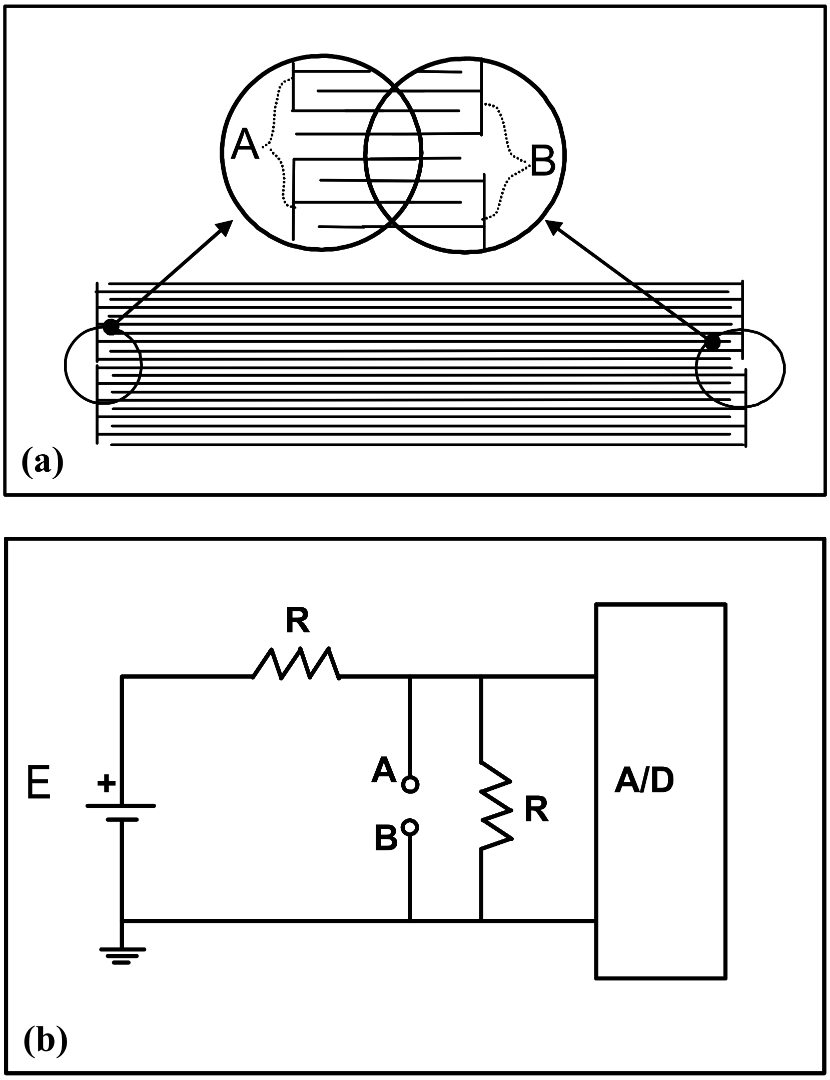

Figure 3.1.3.1. Schematic representation of the foot-switch mat (a) and relevant circuitry (b).

The mat's length (4m) and width (50cm) allowed subjects to walk unconstrained, thus fulfilling the basic requirement of not influencing the subject's way of walking.

The accuracy of the instrument was checked by means of a six-component force plate. Figure 3.1.3.2. shows an example of the typical patterns of three signals: the two acquired from the mat, corresponding to the left and right side, and one acquired from the force platform. As highlighted in the graph below, contact and detachment time of both feet were clearly detected by the mat, with the same accuracy that could be obtained using the force platform. Considering the fact that the mat allows for the measure of more than one stride and that it is a cheaper and easier to use instrument, it has proven to be a suitable tool for the purpose of this study.

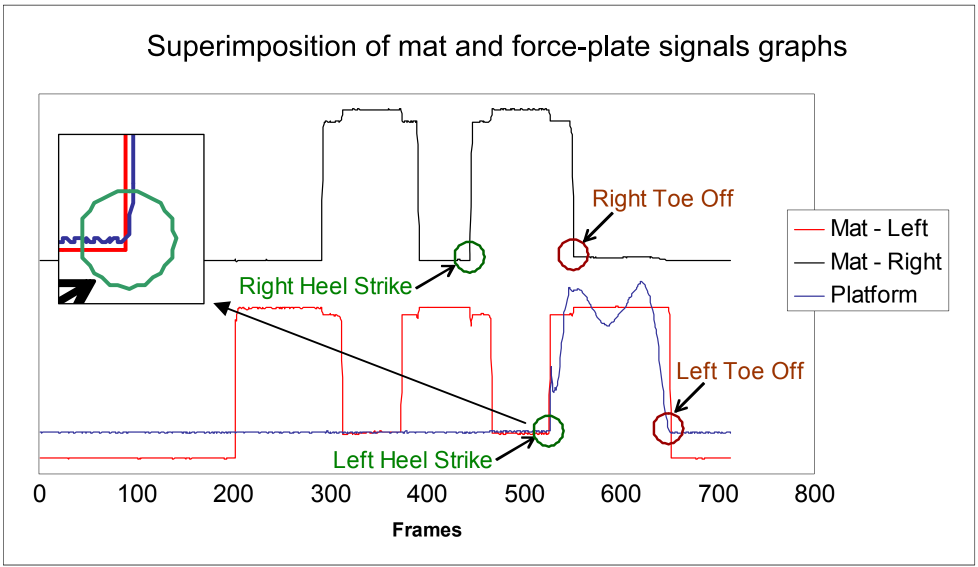

Figure 3.1.3.2. Time pattern of the signals recorded by the mat and the force-plate during walking. The heel-strike and toe-off time instants have been also indicated.

3.1.4. Experimental Protocol

The subjects were asked to walk at two different speeds verbally defined as:

- "Walk at your natural speed" (comfortable)
- "Walk as fast as you can" (fast)

They walked along a 8 m distance: starting 2 m before and stopping 2 m after the mat surface.

While walking, the subjects were instructed to look at a visual target located at the end of the walk path. For each walking speed three trials were carried out and for each trial data regarding two subsequent strides were acquired.

3.1.5. Analysis

To describe the walking cycles in the analysed groups, the following quantities were used:

- Stride length (SL): C7 marker displacement;
- Stride duration (T): was recorded using the mat signals;
- Stride frequency (SF): 1/T;
- Mean speed of progression (V): SL/T.

In many studies, concerning temporal distance parameters related with speed of progression, the parameters were not normalized (Linden 2002, Grieve 1966, Crowninshield 1978); but to avoid to introduce differences in data for subjects of different sizes, and in particular for differences in size between the two groups of subjects, we have normalized the parameters according to the literature (Hof, 1996; Stansfield, 2006; Vaughan, 2003), utilizing dimensionless numbers as follows:

- Stride length (**λ**) = SL/Ll (where Ll is the subject's leg length, measured as the great trochanter height from the floor;
- Stride frequency (**φ**) = SF/ $(g/\mathrm{Ll})^{1/2}$ (where *g* is the gravitational acceleration);
- Speed of progression (ϖ) = V/ $(g{*}\mathrm{Ll})^{1/2}$ (Dimensionless velocity as the square root of the Froude number, Hof and Zijlstra 1997).

The data for an individual subject were averaged across the three trials.

The relationship between the gait spatial-temporal parameters was analysed using bivariate regression analysis. In particular, stride length and stride frequency versus speed of progression were analysed for both groups.

3.2. Results

Speed of progression, stride length, and stride frequency values, measured for both the elderly and the young group, are shown in tables 3.2.1. and 3.2.2. respectively. Maximum, minimum and mean values, together with the relative standard deviations, have been reported for most comfortable and fast walking.

Table 3.2.1. Descriptive analysis of walking stride parameters in the elderly subjects (22) during most comfortable and fast walking.

Elderly subjects	Speed of progression (m/s)		Stride Length (m)		Stride Frequency (stride/s)	
	Comf.	Fast	Comf.	Fast	Comf.	Fast
Mean	1.04**	1.64	1.09**	1.26	0.96**	1.32
SD	0.15	0.18	0.16	0.14	0.13	0.13
min	0.72	1.31	0.65	0.96	0.76	1.14
max	1.27	2.08	1.34	1.45	1.41	1.55

** = P<0.001

Table 3.2.2. Descriptive analysis of walking stride parameters in the young subjects (25) during most comfortable and fast walking.

Young subjects	Speed of progression (m/s)		Stride Length (m)		Stride Frequency (stride/s)	
	Comf.	Fast	Comf.	Fast	Comf.	Fast
Mean	1.31**	2.30	1.38**	1.66	0.95**	1.39
SD	0.25	0.26	0.13	0.15	0.11	0.22
min	0.93	1.81	1.18	1.40	0.72	1.07
max	2.20	2.75	1.69	1.97	1.30	1.85

** = P<0.001

Looking at the raw data, as expected, the elderly subjects showed lower values for speed of progression. Indeed, the recorded walking speed for the elderly was in the ranges 0.7 to 1.3 during normal walking and 1.3 to 2.1 m/s during fast walking. These values were lower than those of the young subjects that showed ranges of 0.9÷2.2 and 1.8÷2.8 m/s, respectively. The young group, more than the elderly group, exhibited a slight overlapping of the two walking speed ranges.

It appears that to sustain the higher speeds of progression, the elderly subjects increased the stride frequency more than the stride length. Indeed, the elderly subjects showed very similar values in stride frequency for both normal and fast walking in comparison with the young group. Instead, the elderly subjects showed lower values of the stride length in comparison with the young subjects both in normal and in fast walking.

The same could be observed in the data, normalized as described above, shown in table 3.2.3., where the percentage differences between fast and comfortable walking data are also shown. Both groups showed an increasing percentage of the **φ** (freq), from comfortable to fast speed of progression, considerably higher than the **λ** (Length).

Table 3.2.3. Descriptive analysis of normalized walking stride parameters in the elderly and young subjects during most comfortable and fast walking.

Elderly

	ϖ	φ (Freq)	λ (Length)
comf	0.35 (±0.05)	0.28 (±0.02)	1.27 (±0.12)
fast	0.56 (±0.06)	0.39 (±0.04)	1.44 (±0.13)
diff %	57.8	40.9	13.4

Young

	ϖ	φ (Freq)	λ (Length)
comf	0.44 (±0.08)	0.29 (0.03)	1.48 (±0.14)
fast	0.76 (±0.09)	0.43 (±0.06)	1.78 (±0.12)
diff %	74.7	46.6	20.5

To assess the relationship existing between the dimensionless speed of progression ϖ and the dimensionless walking spatial-temporal parameters, a bivariate regression analysis was carried out separately for the groups and for the trials relevant to the self selected normal and fast speed of progression. The resulting data are reported in the figures below in which the regression lines and the relative Pearson's product moment are shown.

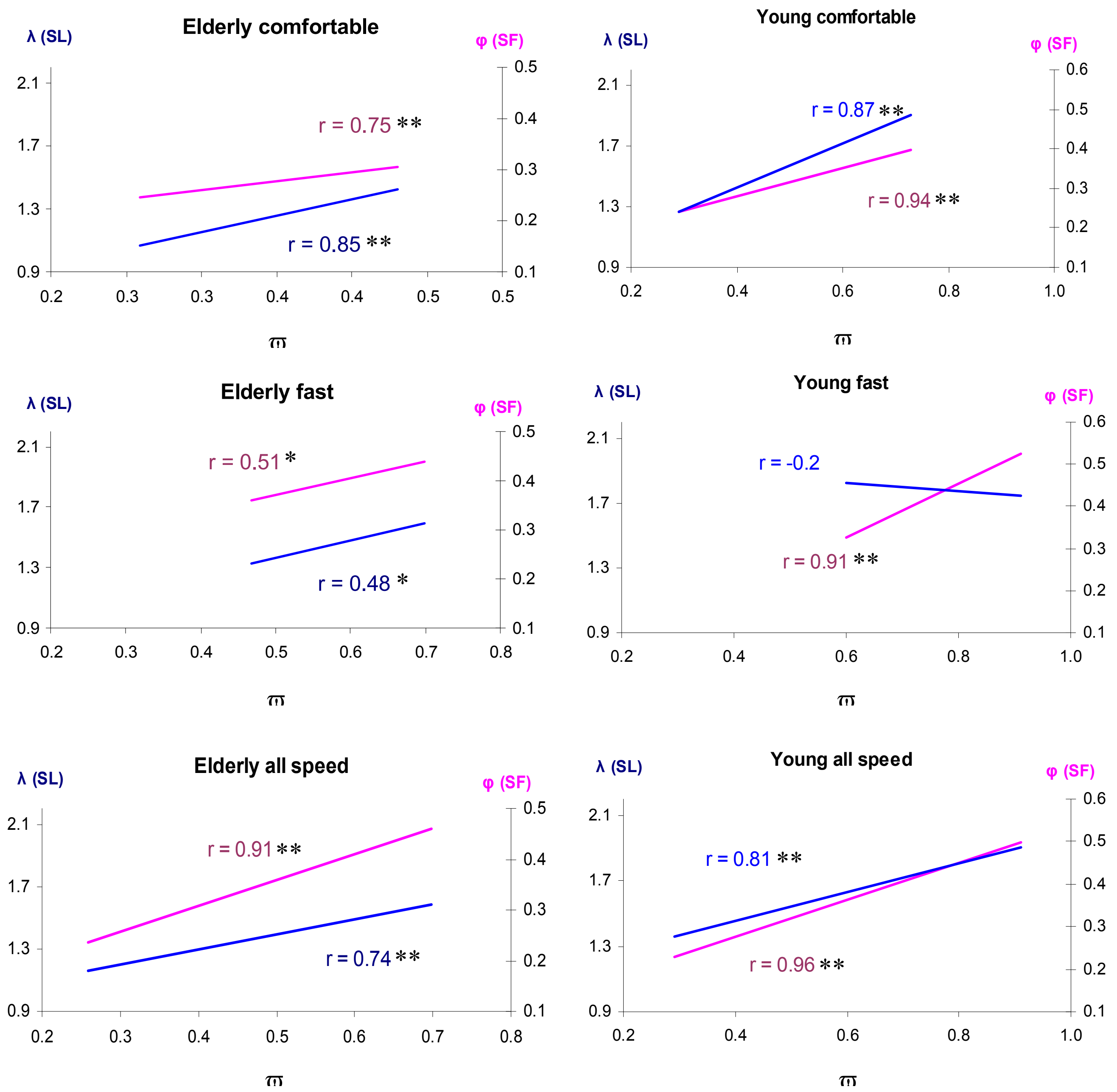

Figure 3.2.1. Regression lines between λ, φ and the dimensionless speed of progression (ϖ) in Young and Elderly Subjects at comfortable and fast speed.

** = P < 0,01   * = P < 0,05

Elderly and young subjects showed some differences in the trend of gait parameters with respects to the variation in speed of progression.

During normal walking both the young and the elderly group showed to increase stride frequency and stride length to sustain higher speed of progression, with high correlation of stride parameters with speed of progression, even if the young group showed a higher correlation value for stride frequencies. Instead, during fast walking, the correlation between speed of progression and the stride parameters were considerably reduced for the elderly group, while the young group maintained high correlation values only for the stride frequencies ($r = 0.9$). No correlation between stride length with speed of progression during fast walking ($r = -0.2$) was shown by the young group during fast walking.

It should be noted that misleadingly strong correlation values have been obtained considering all trials together.

To investigate how the two groups modulated **λ** and **φ** during the two different tasks (comfortable and fastest speed), a bivariate regression analysis was carried out between the two parameters for both groups and the resulting data were plotted as in figures 3.2.2. and 3.2.3.

The two groups showed a different modulation of **λ** and **φ** to sustain changing in speed of progression. At comfortable speed, young group increased **φ** while increasing **λ**, whereas the elderly group showed a similar trend but without any correlation between these two parameters. At fastest speed both groups showed that at higher values of **λ** correspond lower values of **φ**, with the young group showing a higher correlation value, even if these values for both groups were found very low.

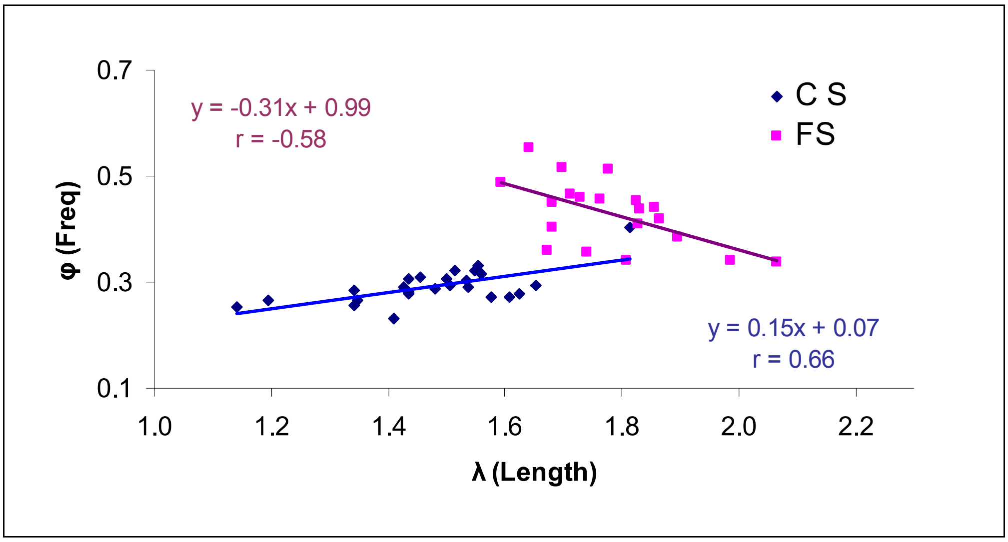

Fig. 3.2.2. Young Group: φ Vs λ in comfortable and fast speed

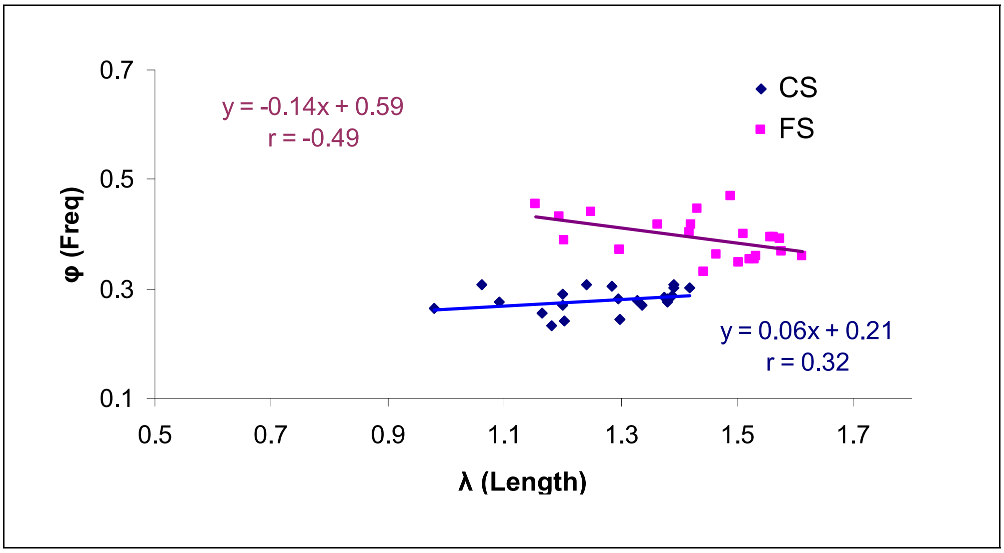

Fig. 3.2.3. Elderly Group: φ Vs λ in comfortable and fast speed

3.3. Discussion

3.3.1. Changes in spatial-temporal gait parameters associated with age and speed

A clear effect of stride length and frequency on speed of progression both in young and elderly subjects was found, which confirmed the results reported in the literature (Sekiya et al. 1997; Danion et al.2003). However, this effect was clearly different in the two sample groups and in the two different tasks performed. Generally, both groups tended to increase walking speed by increasing φ more than λ, but looking in detail some differences come out.

At comfortable speed, the overall behaviour of the two groups can be considered similar, increasing their walking speed by increasing both stride frequency and stride length, but the elderly showed a higher correlation values for the **λ,** while the younger showed a higher correlation values for **φ.**

During fast walking, the differences between elderly and young subjects became more evident. The elderly maintained the same tendency than during comfortable walking, increasing both **λ** and **φ** increasing speed of progression, but with very low correlation values. Instead, the young subject maintained the same high correlation of the **φ** with speed of progression (r=0.9), while no correlation was found between **λ** and speed of progression (r=-0.2).

This behaviour is consistent with the results of Hirasaki et al. (1999), and partially differs from Danion et al. (2003) who reported that “changes in speed during free walking result more from a change in length than in frequency”. This is probably due to a lower maximum speed of progression performed during their evaluations.

Our data suggests that young and elderly people coordinate with both stride length and stride frequency to sustain higher speed of progression, while this is within a range that they perceive as comfortable. Beyond this threshold, they can sustain the efforts picking up from their one’s capabilities, that differs from each other. Indeed, the young subject, at their fastest speed, showed no correlation with **λ,** probably because it is easier for the younger to reach the maximum amplitude in the legs movements, so that they reach the saturation of **λ** before that of **φ** (consistent with Hirasaki 1999).

The decreasing efficiency in the functioning of the elderly people leads to the lower threshold of speed of progression, and their performance relies on their subjective residual functional capabilities, which relates to their health status.

According to Kressig et al. (2004), implications of these findings focus on the need to extend the classification system in older adults beyond age alone to more meaningful and better focused categories based on their functional status in daily activities.

It should be noted that misleadingly strong correlation values have been obtained considering all trials together. Which makes think of how the common way of analyzing data in literature might corrupt the results (Zijlstra 2003, Stansfield 2006).

3.3.2. Stride Frequency and Stride Length modulation

Reported results showed that, as hypothesised, the way young and elderly subjects combine **λ** and **φ** to increase speed of progression strictly depends on the demand of the motor task they have to perform. Both groups showed clear differences, in **λ** and **φ** combination, between comfortable and fast speed of progression. This seems to support the previous thesis that different subjects can support the required efforts with their one's capacity, and that also the older people retain the capacity to modulate the speed of progression and the stride parameters.

From the results of this study, it seems that the increasing in speed of progression supported by an increasing of the spatial-temporal parameters of gait, could be considered an intrinsic gait pattern, that could be put into place by individuals depending on their peculiar characteristics and on the effort required.

In most studies, temporal and spatial parameters of human gait have been treated separately (Sekiya et al. 1997; Maruyama et al. 1992; Goldie et al. 2001), but doing it this way it could be possible to fail to understanding the whole phenomenon of human gait.

These results are consistent with the results of the recent literature: Shkuratova (2004) found that elderly people adjusted differently the walking parameters, “depending on which type of balance demand was encountered”; Li (2005) found that variability in gait appeared to have a structured nature, that suggests that variability could be functional and not just random variations interfering with normal functioning, as in Hausdorff (1997; 1999).

3.4. Conclusions

The equipment used, together with the data analysis procedures, has proved to be a useful tool for the aim of this research. In particular, the option to analyse the relationship between the temporal-spatial walking parameters separately for the two different specific walking tasks, allowed us to highlight some differences between young and elderly subjects in the stride length/frequency modulation to support variation in walking speed. As stated above, these differences could be attributed to a different level of motor capacity between the groups and within them. The latter seems to confirm our starting hypothesis.

But, although some interesting results were achieved, a number of questions are still open:

- Would the same phenomena be observed if, for whatever causes, the subjects were asked to steadily modify their walking speed?
- Without any restrain imposed by the laboratory architecture or experimental protocol, how do the different subjects modify the walking temporal-spatial parameters to modulate the speed of progression?
- Are there some differences in the modulation of temporal-spatial parameters, to modulate the speed of progression, related to the subjects' age?

In order to consolidate the results of the present study, the analysis of walking patterns in a space wider than that of a laboratory, and in more natural conditions, could be a more useful tool. Moreover, the application of an incremental walking speed protocol, could be better to analyse the way people, differently aged, modulate the walking parameters to support variation in walking speed.

4. THE APPLIED STUDY

4. THE APPLIED STUDY

4.1. Methods

4.1.1. Subjects

Two samples of healthy subjects, elderly and young, voluntarily participated in this study. The elderly group was composed by nine females and eight males, while the young sample was composed by fifteen males and thirteen females. All subjects provided informed consent before testing.

Their age, height and body mass data is shown in table 4.1.1.1.

Table 4.1.1.1. Descriptive analysis of the subjects participating in the study

	Elderly group n.17 (9F; 8M)				Young group n.28 (13F; 15M)			
	Age (years)	**Height (cm)**	**Leg Length (cm)**	**Body mass (kg)**	**Age (years)**	**Height (cm)**	**Leg Length (cm)**	**Body mass (kg)**
Mean	67.4	165.3	83.6	74.7	22.1	173.4	93.3	67.4
SD	3.8	7.3	6.0	9.6	2.8	10.1	9.1	12.2

Each subject was submitted to a medical examination certifying the health status; only those having no history of vestibular disease or other disorders that would affect their normal locomotion performance were selected.

4.1.2. Instrumentation

Foot-ground contacts were detected using the GAITRite® system that was available at the “ErgoLab” laboratory in the Physical Activity and Sport Sciences Faculty of the Granada University (Spain). This system is a portable 4.57 m long and 0.90 m wide walkway with pressure sensors embedded in it (Bilney et al. 2003). As the subjects walk over the walkway, the sensors output enable the collection of the data on spatial-temporal gait parameters. The active area of the mat is 3.66 m long and 0.61 m wide. A distance of 12.7 mm separates the centres of the sensors the area of which is 1 cm^2. Data is sampled from the walkway at a frequency of 80 samples per second. The walkway is connected to a PC by an interface cable. The spatial and temporal characteristics of gait, obtained for each step within the entire gait trial, are processed and stored by a PC using GAITRite software. The GAITRite system allows the subject to walk without the encumbrance of wires or markers, allowing for the most natural gait possible (Figure 4.1.2.1.).

Fig. 4.1.2.1. A young subject performing a test

4.1.3. Experimental Protocol

The subjects were asked to walk continuously along a circuit, starting at a speed verbally defined as: “Walk at your natural speed; the most comfortable one”.

At the centre of the circuit (figures 4.1.3.1. and 4.1.3.2.), they had to pass each time over the GAITRite surface and the walking parameters were recorded.

At the end of each 90 s, the subjects were asked to slightly increase their speed of progression; this would go on until they perceived the effort as going from hard to very hard (15/16 in the RPE. Borg’s scale).

After this, a recovery time of 5 min was permitted, before setting off again to run only one way tests, exerted at the maximum possible speed. The latter trial was repeated five times.

The subjects were instructed to look, while walking, at a visual target located at the end of the walking path.

To control the exerted physical effort during the trial, the heart rate was monitored with a Polar pulsometer, starting the test only if the heart rate of the subjects were at a rest level.

The gates made with two cones, before and after the walkway, allowed the subjects to align their walking with the length of the mat. Because of the time needed by the GaitRite software between the successive acquisitions, it was necessary to differentiate the pathways between young and elderly subjects. Therefore, the pathway of the younger was longer than that of the elderly, taking into consideration the higher speed of progression of younger subjects.

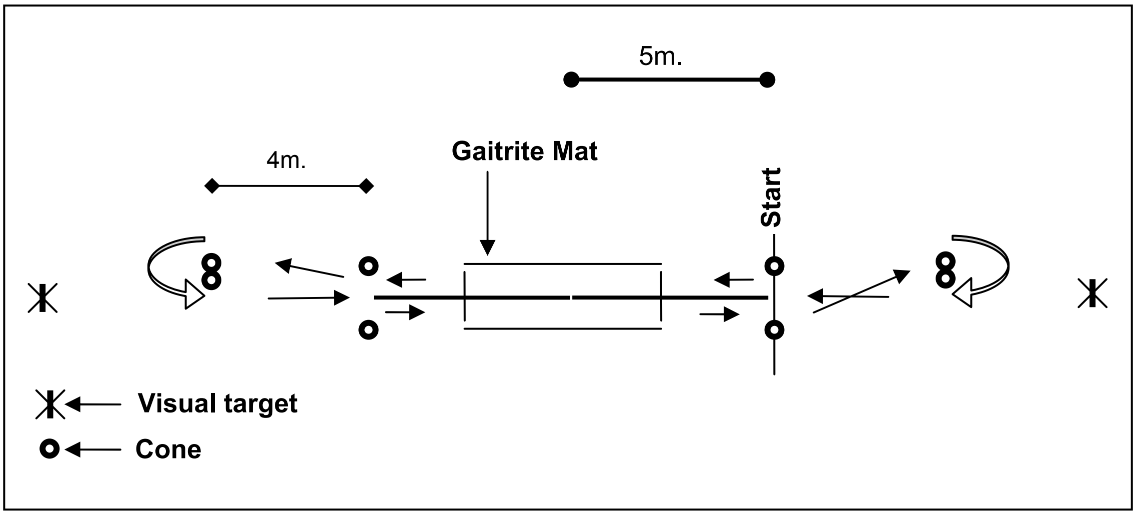

Fig. 4.1.3.1. Elderly person's path

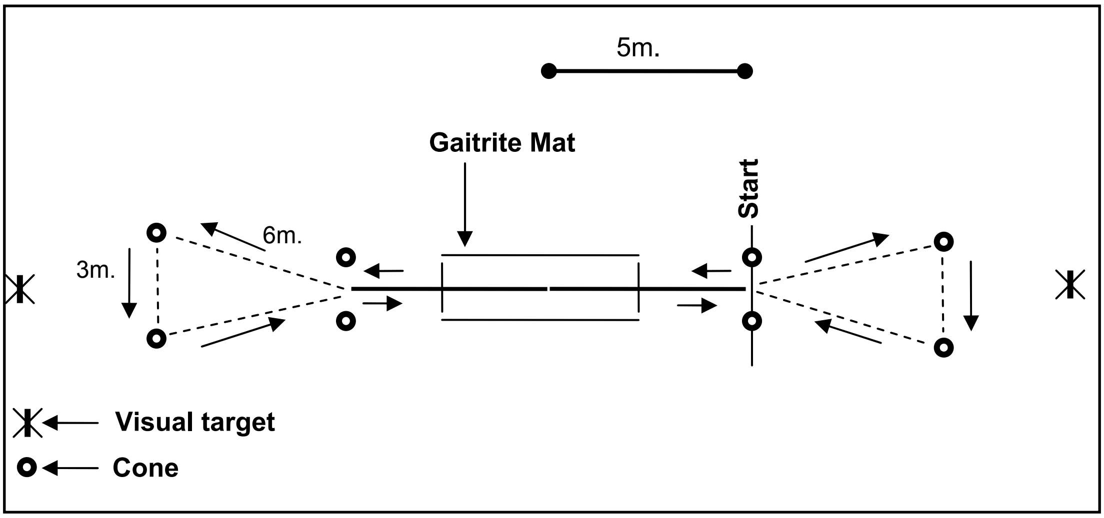

Fig. 4.1.3.2. Young person's path

4.1.4. Analysis

For each subject, the data collected during the self-selected incremental tests, were clustered in terms of 33rd, 66th and 100th percentile of the Zscore of the speed values. Due to the experimental instructions and protocol, the speed exerted at the first range was considered as the most comfortable speed, while it was considered as the mean and the maximum effort for the other speed ranges. This procedure allowed us to compare, for all subjects, the data collected at the same exerted effort, even if the exerted speed could be different. Moreover, the increments of the speed that were asked to the subjects each 1’30” determined a trend of the walking speed with a stairs shape; this could have affected the analysis if it was exerted with a larger subdivision of the speed values. Indeed, the effect of the higher increment of the speed at the moment of the claim, was smoothed by the large period of time that was gotten with our subdivision with respect to a more large subdivision.

The way the subjects modulate speed of progression was determined by the Pearson’s correlation coefficients which were computed between all gait variables and the normalized speed values, for each speed condition and for each subject. Moreover, a linear hierarchical regression between these parameters was conducted, to highlight possible differences in the relationship between the parameters, during the different walking efforts.

Data for the young and older subjects were examined independently by means of Anova to analyze the gait characteristics in each age group.

Differences in gait parameters between the young and older subjects were determined using a series of *t*-tests. Level of significance will be set at $p=0.05$.

Although in the first methodological study there were no differences in the results between the normalized and the not normalized data, in this study too the analysis was applied both at the normalized and the not normalized data; the normalization was made as in the previous study.

4.2. Results

The main recorded parameters are shown in tables 4.2.1. and 4.2.2. for elderly and young subjects, respectively. The mean values, with their relative standard deviations and coefficient of variation, have been reported for each range of the subjects' self-selected speed of progression. In the last three columns, the normalized parameters (as in Hof, 1996) were reported.

Table 4.2.1. Descriptive analysis of walking stride parameters in the elderly subjects (n.17) during an incremental walking speed test, and at maximal speed of progression.

Elderly		Velocity (cm/s)	Cadence (steps/min)	SL mean (cm)	Supp.Base L (cm)	Supp.Base R (cm)	D.Supp.Time mean (s)	V norm ϖ	Cad norm φ	SL norm λ
	Mean	142,94	120,82	142,10	8,97	8,83	0,27	0,50	35,22	1,70
1°-33°	SD	14,25	8,95	12,06	2,61	2,49	0,03	0,05	2,54	0,14
Percentile	CV	0,06	0,04	0,03	0,20	0,19	0,08	0,06	0,04	0,03
	Mean	165,64	131,35	151,66	9,41	9,24	0,23	0,58	38,29	1,82
34°-66°	SD	15,07	8,75	13,43	2,66	2,72	0,03	0,05	2,40	0,15
Percentile	CV	0,04	0,03	0,02	0,17	0,20	0,07	0,04	0,03	0,02
	Mean	182,67	140,12	156,76	9,71	9,59	0,20	0,64	39,97	1,88
67°-100°	SD	18,02	9,11	14,94	2,81	2,79	0,03	0,06	3,60	0,17
Percentile	CV	0,04	0,03	0,02	0,19	0,17	0,09	0,04	0,03	0,02
	Mean	224,23	165,72	162,89	9,18	8,96	0,14	0,78	48,34	1,95
max vel	SD	31,63	15,74	18,91	2,89	3,08	0,04	0,10	4,83	0,21
	CV	0,05	0,05	0,04	0,24	0,22	0,20	0,05	0,05	0,04

Table 4.2.2. Descriptive analysis of walking stride parameters in the younger subjects (n.28) during an incremental walking speed test, and at maximal speed of progression.

Young		Velocity (cm/s)	Cadence (steps/min)	SL mean (cm)	Supp.Base L (cm)	Supp.Base R (cm)	D.Supp.Time mean (s)	V norm ϖ	Cad norm φ	SL norm λ
	Mean	161,48	122,68	157,82	8,95	8,86	0,23	0,54	37,76	1,70
1°-33°	SD	14,66	7,25	10,44	2,21	2,25	0,03	0,05	2,41	0,14
Percentile	CV	0,08	0,04	0,05	0,19	0,20	0,11	0,08	0,04	0,05
	Mean	196,39	135,84	173,80	9,79	9,67	0,18	0,65	41,81	1,87
34°-66°	SD	15,88	8,03	13,07	1,86	1,92	0,02	0,05	2,63	0,12
Percentile	CV	0,04	0,03	0,02	0,17	0,18	0,08	0,04	0,03	0,02
	Mean	222,41	149,70	178,34	10,22	10,04	0,15	0,74	46,24	1,92
67°-100°	SD	19,12	10,00	14,63	2,23	2,29	0,03	0,06	3,63	0,13
Percentile	CV	0,04	0,04	0,02	0,23	0,23	0,12	0,04	0,04	0,02
	Mean	302,02	195,42	187,65	9,27	9,14	0,09	1,00	60,25	2,02
max vel	SD	36,28	22,82	16,28	3,19	3,26	0,03	0,10	8,13	0,15
	CV	0,06	0,09	0,05	0,42	0,56	0,32	0,06	0,09	0,05

Looking at the raw data, we can observe that, as expected, the values of the elderly are lower than those of the younger people, but this is not exactly true for all parameters, as we can observe in table 4.2.3. in which the significance in differences between the young and elderly parameters were reported. The step cadence adopted by the elderly subjects during a most comfortable speed does not have significant differences with the same parameter applied to younger subjects. Most importantly, the elderly people have shown no significant differences with respect to the younger in normalized stride length at each speed condition.

Table 4.2.3. Significance in differences between the parameters of young and elderly people at the three terciles of speed of progression during the incremental test and at the maximal speed.

	1° range	2° range	3° range	max
vel	**	**	**	**
cad	**0**	**0**	*	**
S L	**	**	**	**
Norm vel	*	**	**	**
Norm cad	**	**	**	**
Norm SL	**0**	**0**	**0**	**0**

*** = p<0.05 ** = p<0.01**

Moreover, we can observe that both elderly and young groups have shown that the Coefficient of Variation of the parameters, stay up through the variation in speed of progression.

To analyse the way the subjects modulate the spatial-temporal gait parameters to support variation in walking speed, the Pearson’s correlation coefficients were computed between all gait variables, for each speed range and for each subject. In tables 4.2.4. and 4.2.5. the average correlation coefficients of elderly and young subjects respectively are shown. The data computed between the normalized parameters is also reported.

Table 4.2.4. Mean correlation coefficients between the gait parameters of elderly subjects, at the terciles of speed of progression, collected during a continuous incremental test and at maximal speed of progression.

	mean Correlation Coefficients							
ELDERLY	01-33 perc.le		34-66 perc.le		67-100 perc.le		max vel	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Vel/Cad	0,94	0,05	0,82	0,17	0,81	0,20	0,70	0,40
Vel/SL	0,93	0,03	0,58	0,29	0,46	0,49	0,20	0,57
Cad/SL	0,77	0,15	0,11	0,45	0,00	0,53	-0,32	0,61
Vel/SuppBaseL	0,00	0,36	0,14	0,34	0,07	0,36	0,21	0,15
Vel/SuppBaseR	-0,01	0,38	0,12	0,32	0,12	0,30	0,20	0,14
Vel/DSuppTime	-0,78	0,15	-0,62	0,27	-0,65	0,18	-0,24	0,47
Hof Norm								
Vel/Cad norm	0,94	0,05	0,82	0,17	0,81	0,20	0,70	0,40
Vel/SL norm	0,93	0,03	0,58	0,29	0,46	0,49	0,20	0,57
Cad/SL norm	0,77	0,15	0,11	0,45	0,00	0,53	-0,32	0,61

Table 4.2.5. Mean correlation coefficients between the gait parameters of young subjects, at the terciles of speed of progression, collected during a continuous incremental test and at maximal speed of progression.

	mean Correlation Coefficients							
YOUNG	01-33 perc.le		34-66 perc.le		67-100 perc.le		max vel	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Vel/Cad	0,94	0,11	0,90	0,10	0,85	0,11	0,50	0,40
Vel/SL	0,94	0,12	0,63	0,40	0,28	0,40	0,44	0,27
Cad/SL	0,80	0,33	0,33	0,58	-0,17	0,41	0,38	0,30
Vel/SuppBaseL	0,08	0,38	0,12	0,35	-0,05	0,34	0,21	0,17
Vel/SuppBaseR	0,14	0,34	0,16	0,34	0,04	0,34	0,22	0,12
Vel/DSuppTime	-0,84	0,16	-0,54	0,31	-0,58	0,28	-0,20	0,48
Hof Norm								
Vel/Cad norm	0,94	0,11	0,90	0,10	0,85	0,11	0,50	0,41
Vel/SL norm	0,94	0,12	0,63	0,40	0,28	0,40	0,46	0,27
Cad/SL norm	0,80	0,33	0,33	0,58	-0,17	0,41	0,39	0,32

First of all, we can note that, in both groups, the correlation between the most considered parameters in the literature change when the speed changes, as opposed to parameters such as the support base which showed no correlation with speed. Generally, in both groups the correlation values tend to decrease as speed of progression increases, until it gets to a null correlation at the maximal speed between some parameters. Only the correlation between the velocity and the cadence of the stride, both in elderly and in young subjects, maintains a high value at each speed of progression, even if it shows the above mentioned reduction.

No correlation was observed between the velocity and the step width (Support Base left and right) in either sample group at any speed.

Moreover, we can observe that the elderly people, compared to the younger, showed the same high correlation values between the stride length and cadence with the most comfortable speed of progression. Instead, increasing the speed of progression, they showed a slightly faster decrease of correlation values of the cadence during the incremental test, while they showed a higher correlation value at the maximal speed test. Furthermore, in the comparison with the younger, the elderly subjects showed a faster decrease in the mean correlation values of the speed with the other walking parameters (except the correlation of the stride length at the maximal speed exerted during the incremental test) when they increase the speed of progression, but they showed a concurrent faster increase in standard deviations of the coefficients.

Another aspect that seems to be interesting to underline, is that in either groups the standard deviation of the correlation coefficients, even if it showed very low values at the most comfortable speed, increases considerably the values at the higher speed of progression.

To highlight possible differences in the relationship between the time-distance parameters, during the different walking efforts, a linear hierarchical regression between these parameters was conducted. The data is plotted in the figures below, where the regression lines of the data corresponding to the tercile of speed are shown, and its significance in differences for young and elderly subjects is reported in table 4.2.6.

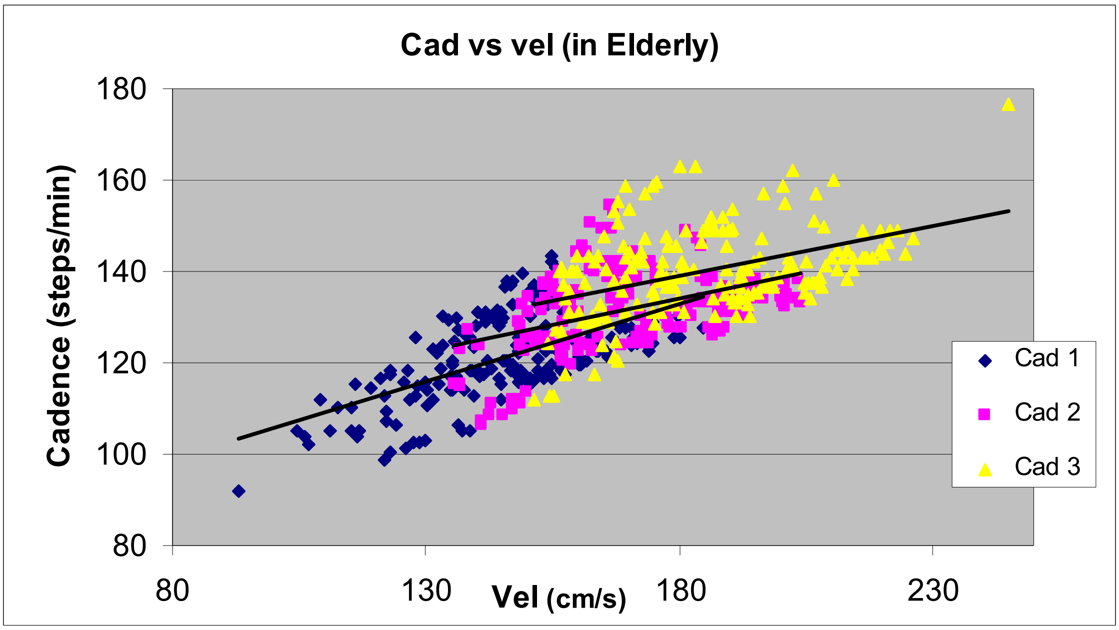

Figure 4.2.1. Scatter plot of the walking cadence versus speed of progression with relative regression lines, in an incremental walking test, divided into terciles of velocity, in elderly.

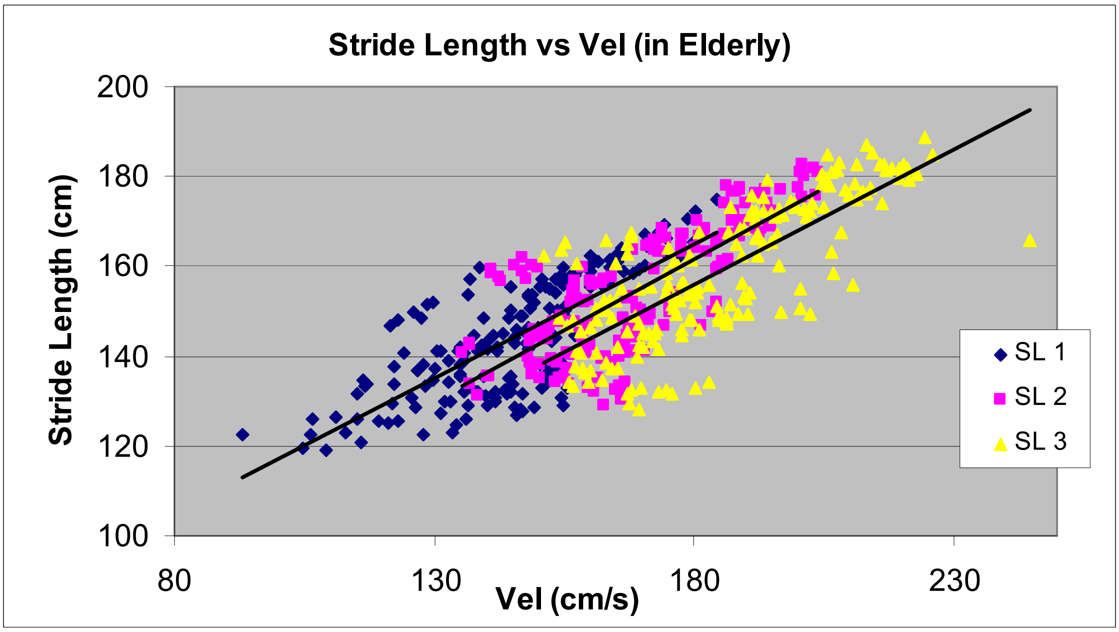

Figure 4.2.2. Scatter plot of the stride length versus speed of progression with relative regression lines, in an incremental walking test, divided into terciles of velocity, in elderly.

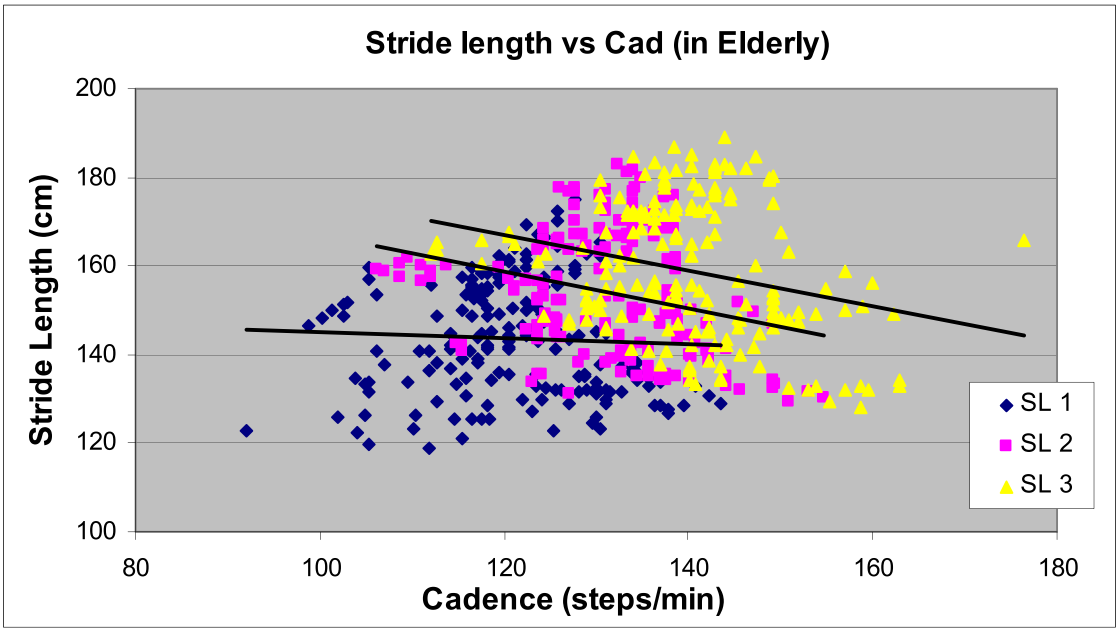

Figure 4.2.3. Scatter plot of the stride length versus walking cadence with relative regression lines, in an incremental walking test, divided into terciles of velocity, in elderly.

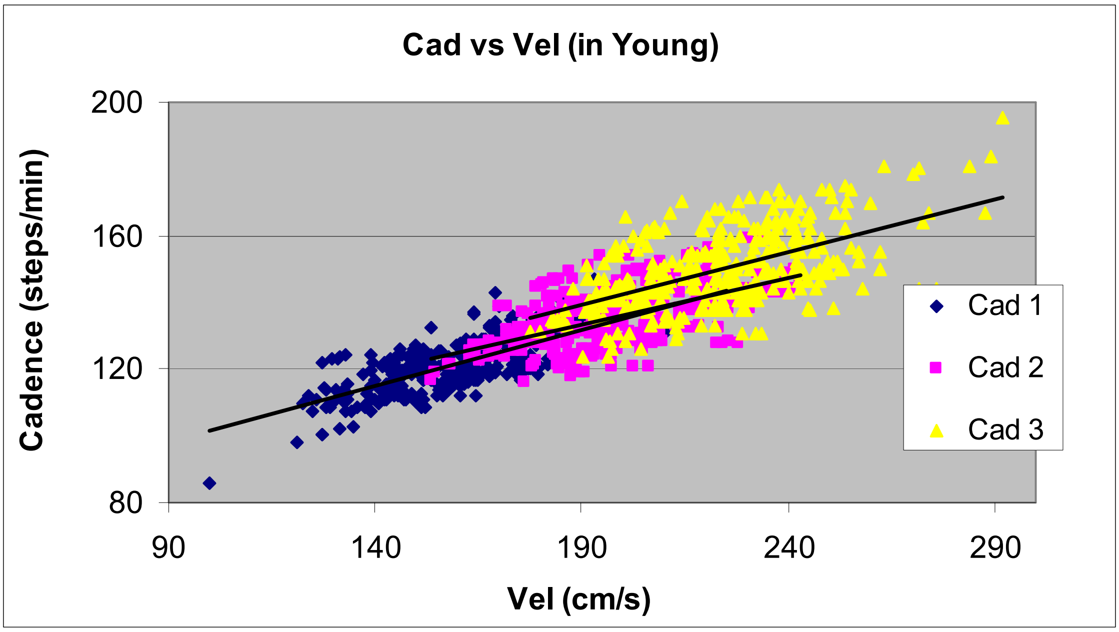

Figure 4.2.4. Scatter plot of the walking cadence versus speed of progression with relative regression lines, in an incremental walking test, divided into terciles of velocity, in young people.

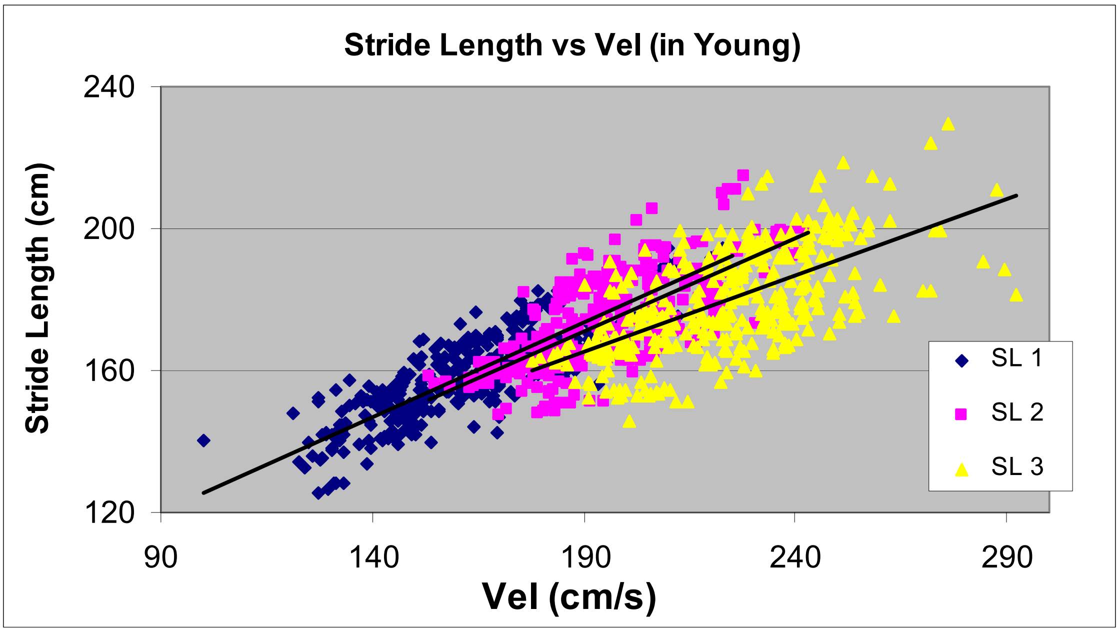

Figure 4.2.5. Scatter plot of the stride length versus speed of progression with relative regression lines, in an incremental walking test, divided into terciles of velocity, in young people.

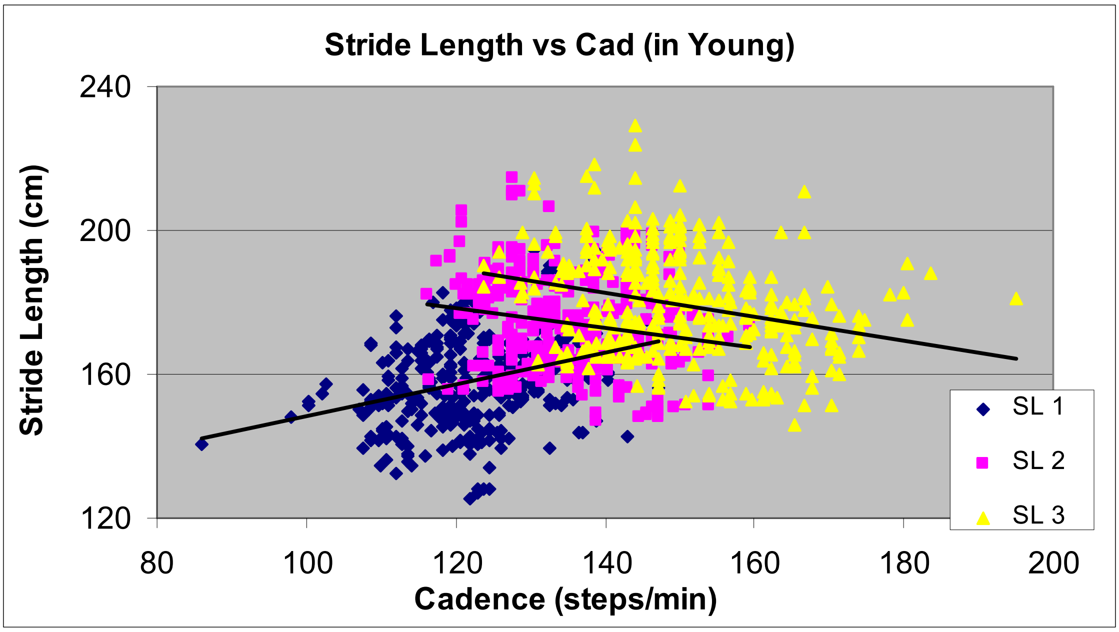

Figure 4.2.6. Scatter plot of the stride length versus walking cadence with relative regression lines, in an incremental walking test, divided into terciles of velocity, in young people.

Table 4.2.6. Significance in differences between the regression model of the considered parameters in the three ranges of speed of progression

	Elderly	Young
Cad Vs Vel	**	**
SL Vs Vel	**	**
SL Vs Cad	**	**

** = p<0.01

From these graphs it appears evident that, in both groups, the way to modulate the walking parameters was different at each speed, and these differences showed a high significance for all the considered paired parameters.

Due to the wide scatter of the data, highlighted in the foregoing graphs, particularly in the maximal speed range, an Anova analysis of the walking time-distance parameters was conducted. The results are summarized in the Table 4.2.7. where the significance of this analysis in the young and elderly subjects were reported.

Table 4.2.7. Significance in Anova Analysis of time-distance walking parameters, in elderly and young groups, collected during an incremental walking test.

	Elderly	Young
Velocity	**	**
Cadence	**	**
St. Length	**	**

** = p<0.01

Both groups showed a high significance of the differences among the variance between and the variance within the subjects, for each parameter. To simply observe the latter circumstance, the walking cadence (that seems to be the parameter that most affects the walking speed) of the young and the elderly group was plotted in the Figures 4.2.7. and 4.2.8. respectively.

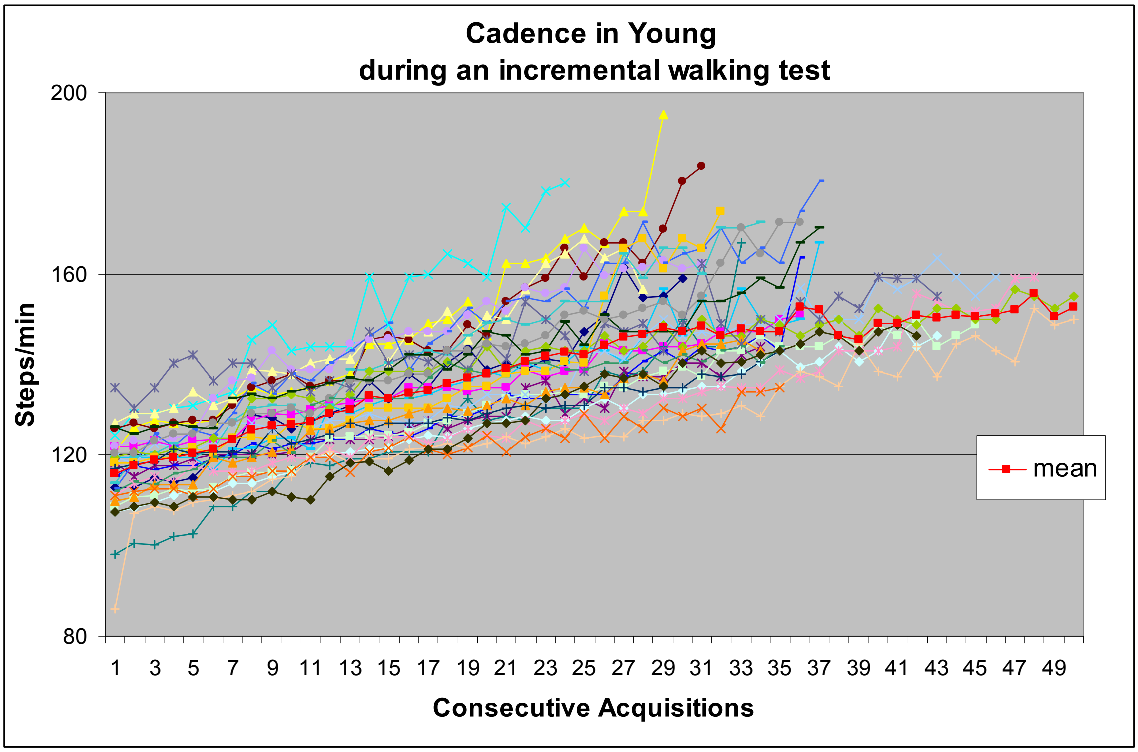

Figure 4.2.7. Scatter plot of cadence data recorded during an incremental walking test in a sample of young subjects. Mean values between subjects with red dots are represented.

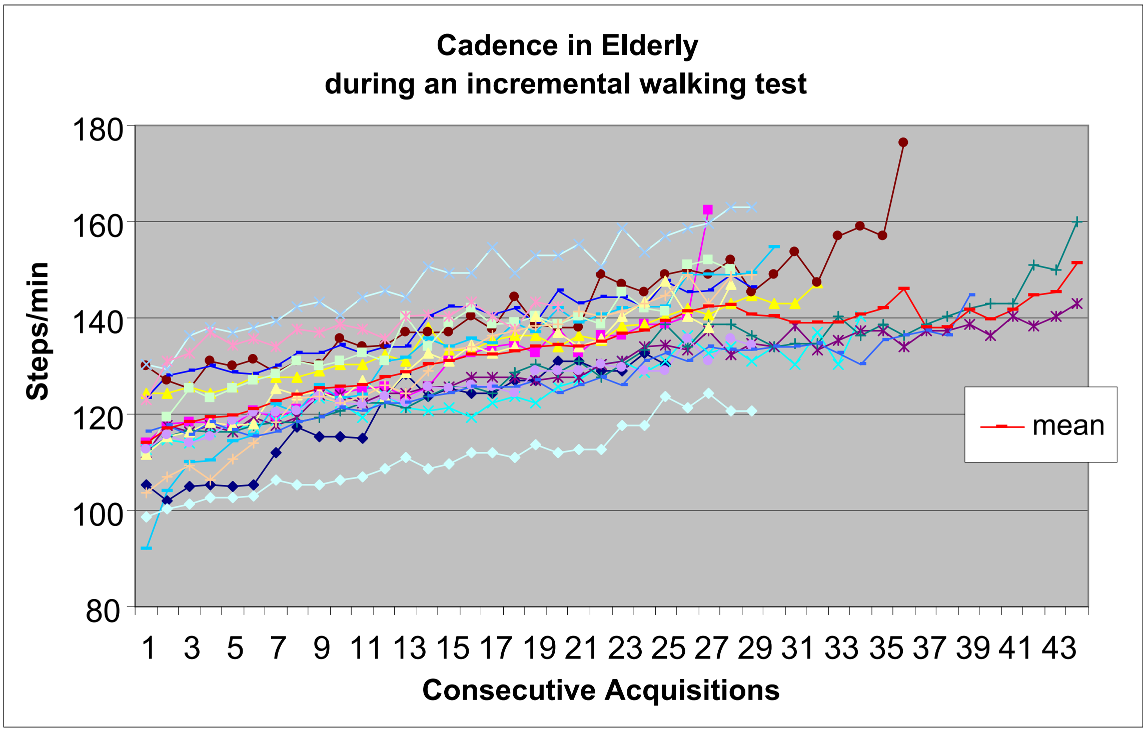

Fig. 4.2.8. Scatter plot of cadence data recorded during an incremental walking test in a sample of elderly subjects. Mean values between subjects with red dots are represented.

It is easy to observe that each subject shows a similar tendency of the cadence progress during the incremental walking test, but each one strayed a lot from the mean values of the group.

4.3. Discussion

4.3.1. Changes in spatial-temporal gait parameters associated with age and speed

Human locomotion is certainly the most analysed movement, and the literature about gait analysis is one of the most prolific topics. But, due to laboratory requirements, the walking parameters were frequently analysed in a walking condition that was not spontaneous, so to affect the walking movement in some way. The most used protocols, entailing walking in a constricted area, the size of which depended on the utilized measurement equipment (Dusing et al. 2007), or entailing walking over a motorized treadmill (Owings et al. 2004; Li et al. 2005; Jordan et al. 2007). Although time-distance parameters for treadmill and over-ground gait were found very similar (Riley et al. 2007), this was demonstrated only at subjects' self selected comfortable speed. Moreover, in the analysis of gait parameters, the most used walking speed observed, was the most comfortable one (Stansfield et al. 2006). In the studies in which the temporal and spatial gait parameters were analysed with respect to the variation in walking speed, the most used protocols utilized, for walking on ground, three self selected speeds (most comfortable, slow and fast speed) (Grabiner et al. 2001; Moe-Nilssen et al. 2004; Hanlon et al. 2006; Mills et al. 2007) or, when treadmill walking was utilized, speed was modified at fixed steps (Zijlstra et al 2003; Li et al. 2005; van Hedel et al. 2006; England et al. 2007). Sometimes the latter steps were determined as function of the self-selected comfortable speed.

To address the aim of this study, it was attempted to rule out any possible conditioning in the subjects' natural walking. The utilized equipment and the extent of the walkway circuit avoided a break in the walking fluidity. In this respect, while no problem was observed for the young subjects, it was not possible for the elderly group to record the heart rate during the entire incremental walking test, due to the difficulty for them to look at the watch of the pulsometer and relate their heart rate while walking, without having repercussions in walking fluidity. This is because, for the elderly, we preferred looking at the heart rate only at the beginning and at the and of the incremental test so as not to affect the walking in any way. Moreover, the applied protocol allowed us to analyse the data, collected during a task that was performed at the same (perceived) effort by each subject (from the most comfortable to the maximum effort). This was done to avoid the problem that the same speed of progression could require different effort for people that have different capability. Furthermore, splitting the data into three speed ranges, and using for the analysis the mean values of each subject, allowed us not to influence the analysis by the different quantity of data collected for each subject (the time that each subject needed to perform the test was different, and the test was performed at a different walking speed, depending on the subject's capability).

The subjects were allowed to walk at a self selected speed, asking them to increase the speed a little each 90 s; it was observed that they responded to the assignments showing highly significant differences between the speed of progression performed at each tercile of speed (Table 4.3.1.1.).

Table 4.3.1.1. Significance in differences of the walking parameters between the ranges of exerted speed in Young and Elderly subjects

	Young			**Elderly**		
	1° Vs 2°	2° Vs 3°	3° Vs Max	1° Vs 2°	2° Vs 3°	3° Vs Max
vel	**	**	**	**	*	**
cad	**	**	**	**	**	**
S L	**	**0**	*	*	**0**	**0**
Norm vel	**	**	**	**	**	**
Norm cad	**	**	**	**	**0**	**
Norm S L	**	**0**	**	*	**0**	**0**

Moreover, all the subjects increased the walking speed to the limit of their capability, indeed, at the end of the incremental walking test, all the subjects showed an heart rate value close to their maximum; in addition, the speed of progression performed by the elderly subjects was on average between 143 cm/s and 224 cm/s, while the same ranged between 161 cm/s and 302 cm/s for the younger. It is interesting to note that these speed values are clearly higher than those performed by other samples of subjects, as reported in the literature (Al-Obaidi et al. 2003, Zijlstra et al. 2003, Owings et al. 2004, England et al. 2007).

Looking at the other time-distance parameters, it was observed that, while the cadence for both groups showed highly significant differences between the speed ranges, it was not the same for the stride length. For the latter parameter, the elderly group showed significant differences only between the first two speed ranges, while any significant differences were shown at the higher speed ranges; the same tendency was shown by the younger group although this tendency showed highly significant differences between the first two speed ranges, and significant differences between the higher speed ranges. This feature could be due to the fact that the elderly people, due to their reduced joint mobility and flexibility (NHMRC 2004), reach saturation of stride length in advance if compared with the younger group (consistent with Hirasaki et al. 1999).

Many times in the literature the differences between the walking parameters of young and elderly people were analysed, and a reduction in the elderly values were highlighted. In this study as well, in general the elderly people showed lower values of the time-distance walking parameters that significantly varied from the parameters of the younger (Tab. 4.2.3.), but this was not true for the normalised stride length that showed no significant differences between the two sample groups; while for the cadence the elderly showed significant differences only in the maximal speed ranges. From this data, it seems that at the most comfortable walking speed, the elderly people could maintain a walking capability close to that of the younger (as in Grabiner et al. 2001), and that it is only the performance conducted over the limits of their "comfortable" capability that could distinguish between elderly and young people.

As we saw above, walking is the most practiced motor skill in man's life. It is performed by means of a rhythmical sequence of the same movement. These features imply that each subject keeps walking with movements that seem to be unvaried. Due to this, many studies have regarded the analysis of variability of the biomechanical aspects of gait, to analyse the motor control of this task. It was highlighted that the stride variability can be affected by many parameters as: combination of stride frequency and stride length (Danion et al. 2003), risk of fall (Hausdorff et al. 1997), fear of falling (Maki 1997), spatial variability (Sekya et al. 1997), temporal variability (Maruyama et al. 1992) etc. In our study, during the continuous incremental test, the coefficients of variation for each parameter in both groups slightly decreased as speed increased; whereas, at the most comfortable speed of progression, the elderly group showed coefficients of variation values slightly lower than the younger group. The latter remark, while differs from some authors (Grabiner et al. 2001; Owings et al. 2004) that observed an increase in the coefficient of variation in older subjects compared to the younger, or when people walked at faster speed, seems to be consistent with Li et al. (2005) who experienced the same and concluded that "the human body is able to use variability as an exploratory means", and that "the increase in the task demands require the motor system to use more resources in completing the prime task (i.e. walking) and effectively limited the ability to use variability as an exploratory tool". Moreover, even though the coefficient of variation of the analyzed parameters showed small values, the standard deviation of the same parameters appeared quite broad. Due to this wide range of subjects' mean data that increases at the faster speed of progression, an analysis of Variance was carried out. As we saw above, both the elderly and the young sample, showed a high significance in differences of the variances within and between the subjects. The two latter results seem to indicate that all people, young or elderly, use a similar manner to manage the walking parameter but with different values between them; probably depending on their own capability. The figures 4.2.7. and 4.2.8. showed very well that the tendency of each subject's data was the same, despite being scattered in a wide range.

4.3.2. Stride Frequency and Stride Length modulation

The walking speed was led to the concurrent modulation of stride length and cadence, and then it is easy to think that, to increase the walking speed, the humans, utilize the concurrent increasing of the other walking parameters. But in the literature, as we discussed previously, there is not an agreement about the matter.

As mentioned, our results highlighted that the increase in spatial-temporal gait parameters to support the increase in speed of progression is a walking pattern that becomes apparent only at the most comfortable walking speed. Indeed, both sample groups showed high correlation values of stride length and cadence with speed of progression only in the most comfortable speed range; as speed increased further, until the limit of their capability, both groups showed a considerable reduction in the correlation values. Anyway, some differences between the parameters and between the different age samples were shown. Particularly, the cadence, maintaining higher correlation values with the walking speed compared to the stride length in both groups, seemed to be the parameter that most affected the increase in speed of progression. Furthermore, the elderly subjects showed the same correlation coefficients of the walking parameters at the most comfortable speed compared to the younger subjects, but they reduced these values faster as speed of progression increased. This seems to be linked to the capability of the elderly subjects to maintain the capacity to respond to the raising of the motor task’s difficulties while the effort is perceived as comfortable. This limit could change depending on their physiological ageing. Moreover, our results highlighted that to the higher mean correlation values between the walking parameters, recorded at the most comfortable speed, correspond the lower standard deviation values between the same parameters; while, increasing walking speed, the mean and standard deviation of the correlation values changed inversely. This confirms that at the most comfortable walking speed all the people similarly manage the walking parameters, but when the physical effort increases, the people respond differently, depending on their own capability. In addition, the correlation of cadence versus stride length showed, in both groups of subjects, significant values only at the most comfortable speed.

It seems important to underline that all the conclusions reported, so far, are supported by the hierarchical regression analysis the results of which are shown in table 4.2.6. This analysis allowed us to highlight the differences in the regression model of each pair of parameters, that showed high significance if considered in the subsequent incremental physical effort. Moreover, this analysis differs from those reported in the literature, where the data are analysed all together (Zijlstra et al. 2003; Brenière 2003; Stansfield et al. 2006). It should be noted that correlation values could be obtained considering all trials together, but this is misleading (Table 4.3.2.1.).

Table 4.3.2.1. Correlation coefficient between the time-distance parameters computed in the whole and in the splitting sample of elderly people. For each sub-group, the mean values between subjects and the whole sample were compared.

ELDERLY	Corr. Coef. 1-33° percentile of Vel		Corr. Coef. 34-66° percentile of Vel		Corr. Coef. 67-100° percentile of Vel		Corr. Coef. 1-100° percentile of Vel
	mean values between subjects	whole sample	mean values between subjects	whole sample	mean values between subjects	whole sample	whole sample
Vel/Cad	0.94	0.45	0.82	0.45	0.81	0.35	0.71
Vel/SL	0.93	0.29	0.58	0.15	0.46	0.17	0.78
Cad/SL	0.77	-0.05	0.11	-0.27	0.00	-0.26	0.12
Vel/SuppBaseL	0.00	0.02	0.14	0.03	0.07	0.05	0.09
Vel/SuppBaseR	-0.01	0.00	0.12	0.04	0.12	0.08	0.10
Vel/DSuppTime	-0.78	-0.44	-0.62	-0.41	-0.65	-0.34	-0.82

One would have to think about this feature, because many times in the literature the data was analysed in this way, not taking into consideration the inter-subject variability.

5. CONCLUSIONS

5. CONCLUSIONS

The present study proved that all people, young and elderly, tend to increase their walking speed increasing both stride length and stride frequency, with a strong correlation between these two walking parameters. While the walking velocity is perceived by each individual subject as comfortable, the correlation between the spatial-temporal walking parameters is shown to be very high. On the other hand, it was observed that a further increase of the walking speed, that seems to be governed by the increase of the stride frequency, resulted in a definite decrease of the correlation values for all subjects. Such motor behaviour was highlighted both for the elderly and the young group, even though a wide inter-subjects variability was noticed.

The results of the present study seem to confirm our hypothesis for which the modulation of stride length and stride frequency to sustain variation in walking speed could constitute an intrinsic pattern of the gait that becomes apparent when the pace is comfortable. For this reason, the way the subjects have to speed up pace depends on the subjective motor capability and then on the required effort. It appears evident that the latter causes a wide inter-subject variability of the gait phenomenon, described very frequently in the literature. The same variability that, when not considered, could lead to misleading conclusions as the authors that dealt with, and tried to solve, the problem of human locomotion.

It is plain from this study that, even though studies about human locomotion are widely reported in the literature, till now, we do not have a complete understanding of the phenomenon. Further studies are certainly needed to consolidate the results of the present work, but only through a variational approach can we identify all the variables involved in human locomotion and, consequently, describe the strategy of the locomotor act. Particularly, it will be interesting to determine the breaking point in stride parameter correlations and, if this threshold exists, it will be interesting to verify if such a limit could be considered as an index of the subject performance capability. To do this, the setting protocol must be further improved with a concurrent acquisition of some physiological parameters, as the heart rate or the breathing gases. A more accurate acquisition of the physiological parameters will allow to compare or to correlate the stride length and cadence modulation with the physical effort during an incremental walking test. It seems important to underline, as we saw above, that the equipment that will be used do not have to interfere with the natural fluidity of the walking in any way. In this sense, equipments with Bluetooth (wireless in general) technology would be preferable. Moreover, the protocol, as it was done in the applied study, has to provide for a self-selected incremental walking test, to allow the subjects to use their actual way to coordinate the walking speed, without any conditioning from the laboratory environment or protocol constraints. Lastly, the inter subjects variability within the tested group has to be considered very well to interpret the data in the right way.

Summary of the Thesis in Spanish

SUMMARY OF THE THESIS IN SPANISH

A continuación anexamos un amplio resumen en español del trabajo. Hemos de indicar que la versión original completa, está en inglés, siendo recomendable utilizar este resumen en español como una guía rápida para la comprensión de la versión original e íntegra de este documento. Al ser éste un resumen, no se han incluido todas las figuras y tablas de la versión integral. Asimismo, la bibliografía se encuentra en la versión completa.

1. INTRODUCCIÓN Y FINALIDAD DEL ESTUDIO

La locomoción humana es una actividad motora fundamental de la vida cotidiana, y ciertamente, es la acción motora más analizada en los laboratorios de análisis del movimiento humano. Por lo tanto, ha sido argumento de una gran cantidad de bibliografía. En particular, la información obtenida observando la longitud de la zancada (SL) y la frecuencia de la zancada (SF) se han utilizado en la bibliografía para describir la locomoción humana, con el fin de distinguir entre paso normal y paso patológico, y para comparar diferentes grupos. No obstante, las conclusiones que han surgido no siempre coinciden; por ejemplo, Danion et al. (2003) observó que la SL y la SF tienen distintos efectos en la variabilidad de la marcha y que los cambios en la velocidad están más relacionados con la SL; mientras Larish et al. (1988) notó que las personas mayores tienden a aumentar la SF más que la SL cuando deben aumentar la velocidad; por el contrario, Breniere (2003) aceptando la correlación de la SL y la SF con la velocidad, demuestra que los sujetos combinan de igual manera la SL y la SF para modificar la velocidad de marcha. Estas discrepancias, a menudo, se deben a la variabilidad de la velocidad de marcha, de la longitud (SL) y de la frecuencia (SF) de la zancada, factores que no son siempre adecuadamente considerados, aunque recientemente la variabilidad de estos parámetros fue observada de manera especifica (Jordan et al 2007; Owings et al 2004*). Además, las restricciones tanto de los laboratorios como de los protocolos experimentales imponen valores a estos parámetros que hacen que la marcha no sea natural y espontánea, influenciando probablemente el análisis (marchar sobre un tapiz rodante; observar algunos parámetros para deducir otros aspectos que no se pueden observar directamente; marchar de una manera establecida con anterioridad).Además, en algunos estudios, los datos han sido analizados sin tener presente el hecho de que los sujetos podrían modificar su forma de regular la SF y la SL según la instrucción recibida; mientras Shkuratova (2004) ha evidenciado que las estrategias de equilibrio durante la marcha son específicas según el requerimiento motor que se determina variando con la edad. Esto se puede verificar cuando se pide a los sujetos un esfuerzo máximo.

En un estudio anterior (Cherubini et al. 2005), la evolución de los parámetros de marcha respecto a las variaciones en la velocidad en dos grupos de personas, ancianos y jóvenes, ha sido claramente diferente en los dos grupos analizados y en las dos diferentes prestaciones analizadas (marcha confortable vs. marcha rápida).

Por esta razón se planteó la hipótesis de que en la marcha humana el aumento de la velocidad, determinado por un aumento de los parámetros espacio-temporales, puede representar un patrón de la marcha que se manifiesta hasta que el esfuerzo es percibido como confortable, por lo tanto, relacionado a las capacidades del sujeto.

El objetivo de este estudio ha sido el de verificar esta hipótesis. Las diferencias entre los sujetos jóvenes y mayores en la modulación de los parámetros de marcha han sido también evidenciadas.

El proyecto ha sido organizado en dos partes con los siguientes objetivos:

- En un primer estudio metodológico han sido identificados los parámetros más adecuados y los procedimientos de análisis.
- En un segundo estudio aplicado, los parámetros precedentemente identificados han sido usados para responder al objetivo de este trabajo.

2. ESTUDIO METODOLÓGICO

2.1. Método

Un grupo joven (YG, n=25, 23±4 años) y un grupo anciano (EG, n=22, 71±4 años) de sujetos sanos han participado en el presente estudio. Se les pidió caminar sucesivamente a dos velocidades a partir de las órdenes: “camina a tu ritmo” (CS) y “camina lo más rápido posible” (FS). Se han realizado tres repeticiones para cada una de las órdenes. Al menos dos pasos fueron extraídos de cada prueba y utilizados para el análisis. Se ha realizado la media individual a partir de los datos de las tres repeticiones.

La duración del paso (T) fue registrada usando una lámina instrumentada, diseñada específicamente (de 4 metros de longitud), que permite a los sujetos caminar de forma libre. La SF se calculó como 1/T. Un sistema VICON 612®, disponible en el laboratorio de biomecánica del IUSM (Rome University Institute for Motor Sciences), fue utilizado para medir la SL (el traslado en dirección anterior-posterior de un marcador reflectante epidérmico posicionado sobre la apófisis espinosa C7). La velocidad (*v*) ha sido calculada como SL/T. Las diferencias determinadas por la antropometría de los sujetos se han tenido en consideración a través de una estandarización de los parámetros estudiados por medio de la longitud de la pierna.

Las relaciones entre los datos estandarizados de SL ($\boldsymbol{\lambda}$), SF ($\boldsymbol{\varphi}$) y *v* (ϖ) fueron analizados usando una regresión bivariable y el coeficiente de correlación de Pearson.

2.2. Resultados

Los valores de *v*, SL y SF, medidos en ambos grupos son mostrados en las tablas 2.2.1. y 2.2.2. respectivamente.

Tabla 2.2.1. Análisis descriptivo de los parámetros de la zancada en sujetos mayores (22) realizando una marcha confortable y una marcha rápida.

Elderly subjects	Speed of progression (m/s)		Stride Length (m)		Stride Frequency (stride/s)	
	Comf.	Fast	Comf.	Fast	Comf.	Fast
Mean	1.04**	1.64	1.09**	1.26	0.96**	1.32
st.dev.	0.15	0.18	0.16	0.14	0.13	0.13
Min	0.72	1.31	0.65	0.96	0.76	1.14
Max	1.27	2.08	1.34	1.45	1.41	1.55

** = P<0.001

Tabla 2.2.2. Análisis descriptivo de los parámetros de la zancada en sujetos jóvenes (25) realizando una marcha confortable y una marcha rápida.

Young subjects	Speed of progression (m/s)		Stride Length (m)		Stride Frequency (stride/s)	
	Comf.	Fast	Comf.	Fast	Comf.	Fast
mean	1.31**	2.30	1.38**	1.66	0.95**	1.39
st.dev.	0.25	0.26	0.13	0.15	0.11	0.22
min	0.93	1.81	1.18	1.40	0.72	1.07
max	2.20	2.75	1.69	1.97	1.30	1.85

** = P<0.001

Observando tales datos, tal y como se esperaba, los sujetos ancianos han mostrado valores mas bajos en *v*.

Además, parece ser que para sostener mayores velocidades de marcha los sujetos ancianos aumentan la SF más que la SL. De hecho, los sujetos ancianos han mostrado valores muy similares en la SF, tanto en la marcha normal como en la más rápida, respecto al grupo joven. En cambio, han mostrado valores más bajos en la SL respecto al grupo joven tanto en la marcha normal como en la rápida.

El mismo aspecto puede ser observado en los datos estandarizados tal y como han sido descritos anteriormente, mostrados en la tabla 2.2.3., donde ha sido calculada también la diferencia porcentual entre la marcha rápida y normal. Ambos grupos han mostrado un incremento porcentual de la **φ**, comparando las dos velocidades de marcha, considerablemente mayor respecto la **λ.**

Tabla 2.2.3. Análisis descriptivo de parámetros normalizados de marcha en sujetos mayores y jóvenes realizando una marcha confortable y una marcha rápida.

Elderly

	ϖ	φ (Freq)	λ (Length)
comf	0.35	0.28	1.27
fast	0.56	0.39	1.44
diff %	57.8	40.9	13.4

Young

	ϖ	φ (Freq)	λ (Length)
comf	0.44	0.29	1.48
fast	0.76	0.43	1.78
diff %	74.7	46.6	20.5

Los datos hallados de la relación existente entre ϖ y los parámetros estandarizados espacio-temporales usando un análisis de regresión bivariable son mostrados en la figura 2.2.1 en la cual se muestra la recta de regresión y los correspondientes coeficientes de correlación de Pearson.

Los grupos de ancianos y jóvenes han mostrado algunas diferencias en la evolución de los parámetros de marcha respecto a las variaciones en *v*. Durante la marcha libre ambos grupos han mostrado un aumento de **φ** (r=0.75; r=0.94 respectivamente) y de **λ** (r=0.85; r=0.87 respectivamente) para sostener una mayor velocidad de marcha.

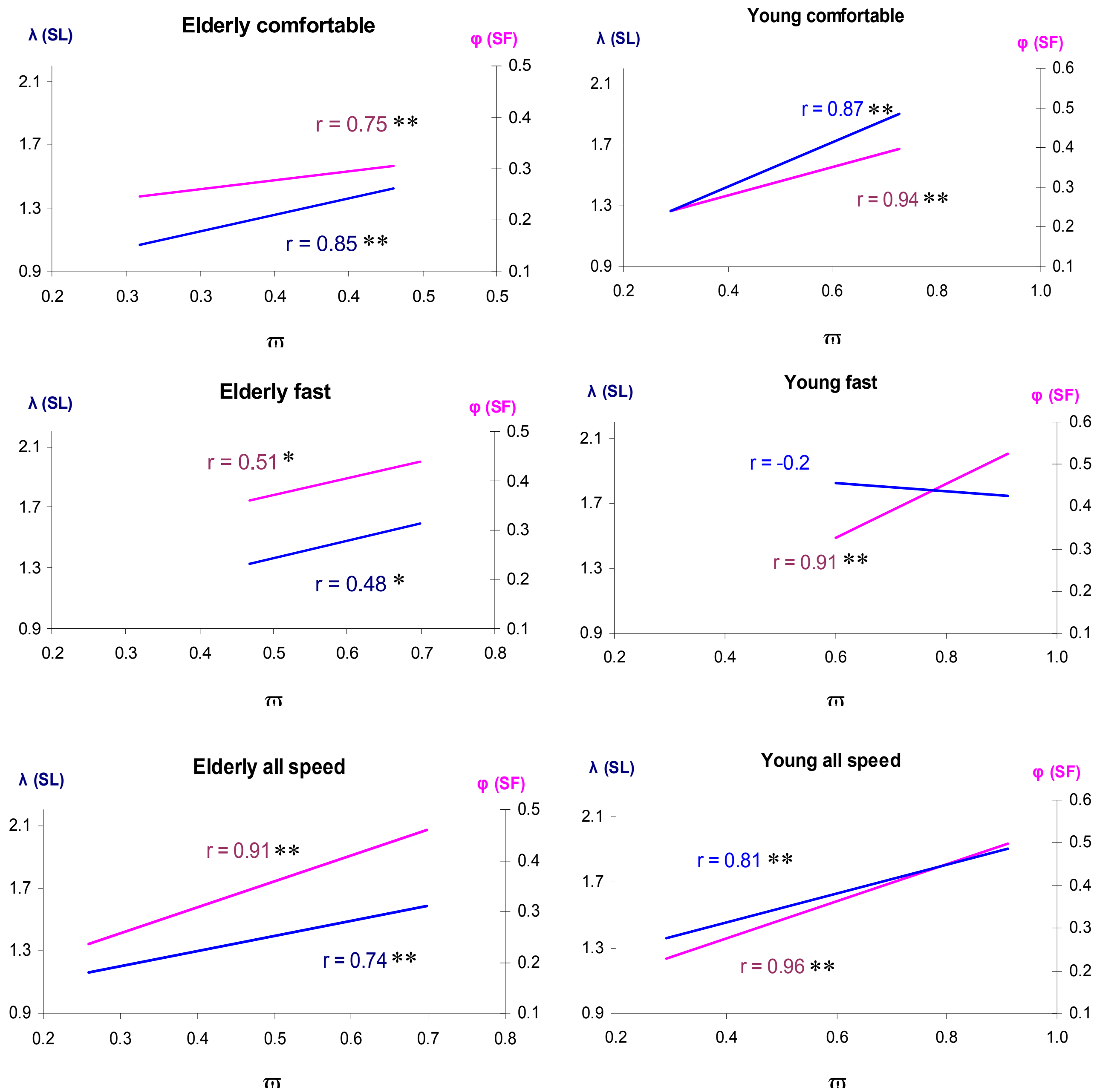

Figura 2.2.1. Líneas de regresión entre **λ**, **φ** y velocidad de desplazamiento sin dimensión (**ϖ**) en sujetos jóvenes y mayores realizando marcha a velocidad confortable y rápida. ** = P < 0,01 * = P < 0,05

En cambio, durante la marcha rápida la correlación entre *v* y los parámetros de marcha se ha reducido considerablemente en el grupo de los ancianos, mientras el grupo joven mantiene una alta correlación entre los valores sólo en la **φ** (r = 0.91), y ninguna correlación para la **λ** (r = -0.2). Es interesante destacar que los valores de correlación calculados tomando en cuenta todas las pruebas realizadas, resultaron engañosamente altos tanto en el grupo de ancianos como en el de jóvenes.

Para indagar cómo los dos grupos modulan **λ** y **φ** durante las dos diferentes velocidades de marcha, el análisis de regresión bivariable ha sido conducido entre los dos parámetros de ambos grupos y los resultados son representados en las Figura 2.2.2. y 2.2.3.

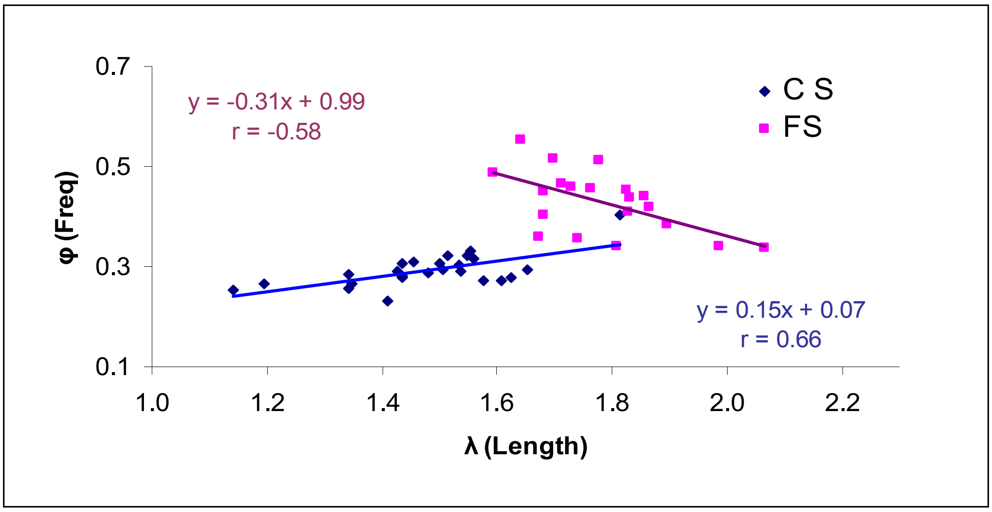

Figura 2.2.2. Grupo joven: φ vs λ en velocidad confortable y rápida.

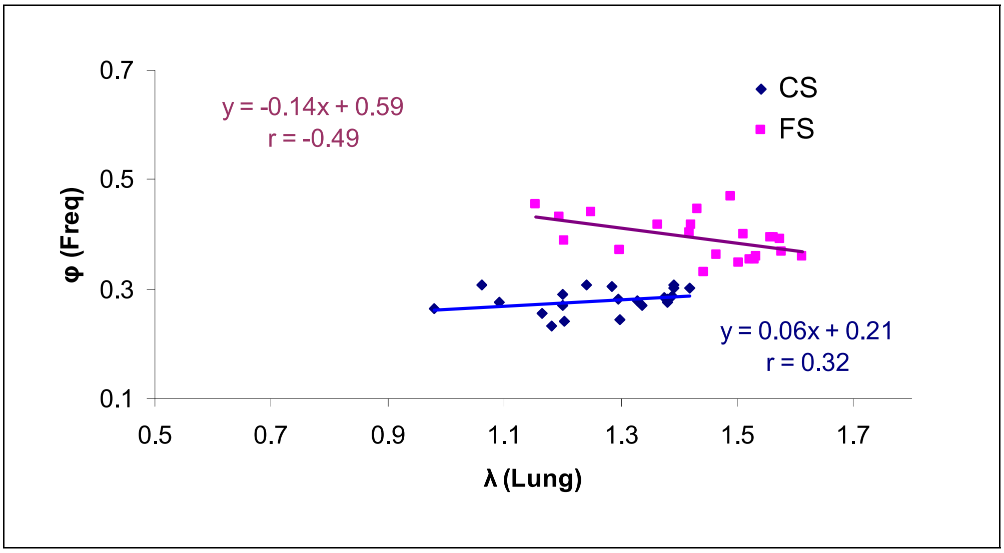

Figura 2.2.3. Grupo mayores: φ vs λ en velocidad confortable y rápida.

Los dos grupos han mostrado similares marchas, ya sea en la velocidad normal, como en la rápida: durante la marcha libre han mostrado que a los valores más altos de **λ** corresponden los valores mas altos de **φ**, mientras en la marcha rápida han mostrado que a los valores mas altos de **λ** corresponden los valores mas bajos de **φ**. Los sujetos ancianos han mostrado valores de correlación más bajos en los dos tipos de marcha.

2.3. Discusión

Tal como se ha planteado en la hipótesis, el modo en el cual los jóvenes y ancianos combinan **φ** y **λ** para aumentar la velocidad de marcha ha sido claramente diferente en los dos grupos analizados y en las dos diferentes prestaciones. Un claro efecto de **φ** y **λ** sobre la velocidad de marcha ha sido hallado pero la correlación entre los parámetros ha sido reducida al incremento de la velocidad.

Generalmente, ambos grupos tienden a aumentar la velocidad de marcha aumentando **φ** más que **λ**, pero observando detalladamente se evidencian algunas diferencias, en particular, durante la marcha rápida.

Este hecho sugiere que las personas jóvenes y aquellas ancianas coordinan tanto la longitud del paso como la frecuencia del paso para sostener una mayor velocidad de marcha, hasta que ésta se encuentra en un rango que es percibido como confortable.

Más allá de este límite, ellos pueden mantener el esfuerzo acudiendo a sus propias capacidades que se diferencian unas de otras. De hecho, los sujetos jóvenes a mayor velocidad, no han mostrado ninguna correlación con la **λ,** probablemente porque es más fácil para los jóvenes alcanzar la máxima amplitud en los movimientos de las piernas, de modo que alcanzan la saturación de la **λ** antes que de la **φ** (de acuerdo con Hirasaki et al. 1999).

El decrecimiento de la eficiencia en las funciones de las personas ancianas conlleva a un límite de velocidad de marcha más bajo y sus prestaciones se sostienen a partir de las capacidades funcionales residuales, propias de cada uno, que se relacionan a sus estados de salud.

Se debe destacar que los valores de correlación calculados, tomando en cuenta todas las pruebas realizadas, resultaron falsamente altos, tanto en el grupo de ancianos como en el de jóvenes. Se debería reflexionar en esta cuestión, ya que muchas veces en literatura los datos son analizados de este modo (Zijlstra et al. 2003; Stansfield et al. 2006).

De los resultados de este estudio, se presume que el aumento en la velocidad de marcha, sostenido por un aumento de los parámetros espacio temporales de ésta, puede ser considerado como un factor intrínseco de la marcha, representado por las caracteristicas propias de las diversas personas, en relación al esfuerzo requerido.

Estos resultados coinciden con los resultados de una literatura reciente: Shkuratova (2004) ha encontrado que las personas ancianas modifican los parámetros de marcha “en relación al tipo de equilibrio requerido”; Li (2005) encontró que la variabilidad en la marcha se manifiesta al encontrar una naturaleza estructurada, que sugiere que la variabilidad podría ser funcional y no solamente una variación ocasional que interfiere con la funcionalidad normal, como afirma Hausdorff (1997; 1999).

2.4 Conclusiones

Los instrumentos utilizados, junto a los procedimientos de análisis de los datos, resultaron útiles para el objetivo de esta investigación. En particular, la opción de analizar separadamente las relaciones entre los parámetros espacio-temporales de la marcha entre las dos prestaciones motoras requeridas, han permitido evidenciar algunas diferencias entre los sujetos jóvenes y los ancianos en la modulación de la longitud y la frecuencia del paso al momento de soportar las variaciones de la velocidad de marcha. Como hemos dicho anteriormente, estas diferencias podrían ser atribuidas a una diversa capacidad motora entre los grupos de sujetos y entre los sujetos de un mismo grupo. Esto parece confirmar nuestra hipótesis inicial.

Si bien se han alcanzado algunos resultados interesantes, quedan abiertas algunas interrogantes:

- ¿Se podría observar el mismo fenómeno si, por alguna razón, a los sujetos se les pidiera que modifiquen progresivamente su velocidad de marcha?
- ¿Sin ninguna restricción impuesta por la arquitectura de laboratorio o por los protocolos experimentales, cómo modificarían los distintos sujetos los parámetros espacio-temporales de marcha para regular la velocidad de marcha?.
- ¿Existen algunas diferencias en el modo de coordinar los parámetros de marcha, para aumentar aún más la velocidad, en relación a la edad de los sujetos?

El análisis de los parámetros de marcha adquiridos en un espacio más amplio que el de un laboratorio y en condiciones de marcha más naturales, podría ser un instrumento útil para consolidar los resultados del presente trabajo. Además, la aplicación de un protocolo de marcha a velocidad incrementada podría ser más eficaz para analizar las maneras que adoptan las personas de edades diversas para modular los parámetros de marcha con el fin de modificar la velocidad de progresión.

3. ESTUDIO APLICADO

3.1. Método

Dos grupos de sujetos sanos, uno de ancianos (EG, n=17, 67±4 años) y uno de jóvenes (YG, n=28, 22±3 años) han participado voluntariamente en el presente estudio.

Todos los sujetos fueron sometidos a una evaluación médica para verificar el estado de salud. Fueron seleccionados sólo aquellos que resultaron exentos de alteraciones vestibulares u otras alteraciones que habrían podido influenciar la normal locomoción. Se les pidió caminar continuamente a lo largo de un circuito, partiendo a una velocidad más confortable para ellos y aumentando paulatinamente la velocidad de marcha, cada 90 s, hasta que percibían el esfuerzo entre fuerte y muy fuerte. Después de un periodo de 5 minutos para descansar, realizaron otra prueba a la máxima velocidad de marcha. Esta última prueba fue repetida 5 veces. En el centro del circuito fue colocado un sistema GAITRite® (Bilney et al. 2003). El sistema GAITRite es un tapiz con sensores de presión incrustados. Durante la andadura de los sujetos a lo largo del tapiz, la señal de salida de los sensores permitió recoger los datos de los parámetros espacio-temporales de la marcha. De este modo, se permitió a los sujetos caminar sin el estorbo de cables o indicadores, eliminando toda posibilidad de condicionamiento de la marcha natural del sujeto.

Para cada sujeto, los datos del test de incremento de velocidad han sido reagrupados en relación al 33, 66 y 100 percentil del Z-score de la velocidad de marcha. Este procedimiento nos ha permitido comparar los datos recogidos en función del esfuerzo efectuado, por igual, por cada uno de los sujetos, independientemente de su velocidad de marcha. La manera como los sujetos modulan la velocidad de marcha fue determinada por medio del coeficiente de correlación de Pearson, entre los parámetros de la marcha, calculado por cada grupo de velocidad y por cada sujeto. Además, un análisis de regresión jerárquica lineal ha sido efectuado para evidenciar posibles diferencias en las relaciones entre los parámetros durante las distintas fases de esfuerzo de la marcha.

Los datos de los sujetos jóvenes y mayores fueron examinados independientemente por medio de un análisis Anova para observar características de marcha en cada grupo de edad

3.2. Resultados

Los principales parámetros de marcha adquiridos se pueden ver en las tablas 3.2.1. y 3.2.2. para los sujetos ancianos y jóvenes respectivamente. Los valores medios, con las relativas desviaciones estándar y coeficientes de variaciones, están señalados por cada rango de velocidad de progresión.

Tabla 3.2.1. Análisis descriptivo de los parámetros de marcha en sujetos mayores (n.17) durante el test de marcha a velocidad incremental, y a la maxima velocidad de desplazamiento.

Elderly		Velocity (cm/s)	Cadence (steps/min)	SL mean (cm)	Supp.Base L (cm)	Supp.Base R (cm)	D.Supp.Time mean (s)	V norm ϖ	Cad norm φ	SL norm λ
	Mean	142,94	120,82	142,10	8,97	8,83	0,27	0,50	35,22	1,70
1°-33°	SD	14,25	8,95	12,06	2,61	2,49	0,03	0,05	2,54	0,14
Percentile	CV	0,06	0,04	0,03	0,20	0,19	0,08	0,06	0,04	0,03
	Mean	165,64	131,35	151,66	9,41	9,24	0,23	0,58	38,29	1,82
34°-66°	SD	15,07	8,75	13,43	2,66	2,72	0,03	0,05	2,40	0,15
Percentile	CV	0,04	0,03	0,02	0,17	0,20	0,07	0,04	0,03	0,02
	Mean	182,67	140,12	156,76	9,71	9,59	0,20	0,64	39,97	1,88
67°-100°	SD	18,02	9,11	14,94	2,81	2,79	0,03	0,06	3,60	0,17
Percentile	CV	0,04	0,03	0,02	0,19	0,17	0,09	0,04	0,03	0,02
	Mean	224,23	165,72	162,89	9,18	8,96	0,14	0,78	48,34	1,95
max vel	SD	31,63	15,74	18,91	2,89	3,08	0,04	0,10	4,83	0,21
	CV	0,05	0,05	0,04	0,24	0,22	0,20	0,05	0,05	0,04

Tabla 3.2.2. Análisis descriptivo de los parámetros de marcha en sujetos jóvenes (n.28) durante el test de marcha a velocidad incremental, y a la maxima velocidad de desplazamiento.

Young		Velocity (cm/s)	Cadence (steps/min)	SL mean (cm)	Supp.Base L (cm)	Supp.Base R (cm)	D.Supp.Time mean (s)	V norm ϖ	Cad norm φ	SL norm λ
	Mean	161,48	122,68	157,82	8,95	8,86	0,23	0,54	37,76	1,70
1°-33°	SD	14,66	7,25	10,44	2,21	2,25	0,03	0,05	2,41	0,14
Percentile	CV	0,08	0,04	0,05	0,19	0,20	0,11	0,08	0,04	0,05
	Mean	196,39	135,84	173,80	9,79	9,67	0,18	0,65	41,81	1,87
34°-66°	SD	15,88	8,03	13,07	1,86	1,92	0,02	0,05	2,63	0,12
Percentile	CV	0,04	0,03	0,02	0,17	0,18	0,08	0,04	0,03	0,02
	Mean	222,41	149,70	178,34	10,22	10,04	0,15	0,74	46,24	1,92
67°-100°	SD	19,12	10,00	14,63	2,23	2,29	0,03	0,06	3,63	0,13
Percentile	CV	0,04	0,04	0,02	0,23	0,23	0,12	0,04	0,04	0,02
	Mean	302,02	195,42	187,65	9,27	9,14	0,09	1,00	60,25	2,02
max vel	SD	36,28	22,82	16,28	3,19	3,26	0,03	0,10	8,13	0,15
	CV	0,06	0,09	0,05	0,42	0,56	0,32	0,06	0,09	0,05

En las últimas tres columnas, los valores normalizados (como en Hof 1996) han sido señalados.

En general, podemos observar que los valores de los sujetos ancianos son más bajos que los de los sujetos más jóvenes, pero esto no es completamente cierto para todos los parámetros, como podemos ver en la tabla 3.2.3. Sobre todo, los sujetos ancianos no han mostrado diferencias significativas respecto a los más jóvenes en cuanto a la longitud del paso normalizada, en cada condición de velocidad.

Tabla 3.2.3. Significación en las diferencias entre los parámetros de jóvenes y mayores en los tres terciles de la velocidad de marcha durante el test incremental y en la maxima velocidad.

	1° range	2° range	3° range	max
vel	**	**	**	**
cad	**0**	**0**	*	**
S L	**	**	**	**
Norm vel	*	**	**	**
Norm cad	**	**	**	**
Norm SL	**0**	**0**	**0**	**0**

*** = p<0.05   ** = p<0.01**

En las tablas 3.2.4. y 3.2.5. están recogidos los coeficientes de correlación medios entre las variables de marcha, por cada rango de velocidad y por cada sujeto, tanto en el grupo de ancianos como en el grupo de jóvenes.

Tabla 3.2.4. Coeficientes de correlación medios de los parámetros de la marcha de sujetos mayores, en los tres rangos de velocidad, obtenidos durante el test incremental y a maxima velocidad.

ELDERLY	mean Correlation Coefficients 01-33 perc.le		34-66 perc.le		67-100 perc.le		max vel	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Vel/Cad	0,94	0,05	0,82	0,17	0,81	0,20	0,70	0,40
Vel/SL	0,93	0,03	0,58	0,29	0,46	0,49	0,20	0,57
Cad/SL	0,77	0,15	0,11	0,45	0,00	0,53	-0,32	0,61
Vel/SuppBaseL	0,00	0,36	0,14	0,34	0,07	0,36	0,21	0,15
Vel/SuppBaseR	-0,01	0,38	0,12	0,32	0,12	0,30	0,20	0,14
Vel/DSuppTime	-0,78	0,15	-0,62	0,27	-0,65	0,18	-0,24	0,47
Hof Norm								
Vel/Cad norm	0,94	0,05	0,82	0,17	0,81	0,20	0,70	0,40
Vel/SL norm	0,93	0,03	0,58	0,29	0,46	0,49	0,20	0,57
Cad/SL norm	0,77	0,15	0,11	0,45	0,00	0,53	-0,32	0,61

Tabla 3.2.5. Coeficientes de correlación medios de los parámetros de la marcha de sujetos jóvenes, en los tres rangos de velocidad, obtenidos durante el test incremental y a maxima velocidad.

YOUNG	mean Correlation Coefficients 01-33 perc.le		34-66 perc.le		67-100 perc.le		max vel	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Vel/Cad	0,94	0,11	0,90	0,10	0,85	0,11	0,50	0,40
Vel/SL	0,94	0,12	0,63	0,40	0,28	0,40	0,44	0,27
Cad/SL	0,80	0,33	0,33	0,58	-0,17	0,41	0,38	0,30
Vel/SuppBaseL	0,08	0,38	0,12	0,35	-0,05	0,34	0,21	0,17
Vel/SuppBaseR	0,14	0,34	0,16	0,34	0,04	0,34	0,22	0,12
Vel/DSuppTime	-0,84	0,16	-0,54	0,31	-0,58	0,28	-0,20	0,48
Hof Norm								
Vel/Cad norm	0,94	0,11	0,90	0,10	0,85	0,11	0,50	0,41
Vel/SL norm	0,94	0,12	0,63	0,40	0,28	0,40	0,46	0,27
Cad/SL norm	0,80	0,33	0,33	0,58	-0,17	0,41	0,39	0,32

Generalmente, en ambos grupos, los valores de estas correlaciones tienden a reducirse al aumentar la velocidad de progresión, hasta llegar a un valor nulo evidenciado a la máxima velocidad, entre algunos parámetros. Solamente la correlación entre la velocidad y la frecuencia del paso, ya sea en los ancianos como en los jóvenes, mantiene valores altos en cada rango de velocidad, aunque se manifiesta la citada reducción a velocidades mayores.

Además, en comparación con los más jóvenes, los sujetos ancianos han mostrado una reducción más rápida de los valores medios de correlación de la velocidad con respecto a los otros parámetros de marcha (excepto el de la longitud del paso registrada a la máxima velocidad del test incremental) al aumentar la velocidad de progresión, pero han mostrado un simultáneo y rápido incremento de la desviación estándar de los mismos coeficientes de correlación.

Para evidenciar posibles diferencias en las relaciones entre los parámetros espacio-temporales de la andadura, durante la marcha prolongada con diferente esfuerzo, se ha llevado a cabo un análisis de regresión jerárquica entre los mismos parámetros. Los datos han sido registrados en los gráficos mostrados a continuación, donde están representadas las líneas de regresión entre los mismos parámetros en los tres rangos de velocidad, mientras que lo significativo de sus diferencias tanto para los sujetos jóvenes como para los ancianos, se puede ver en la tabla 3.2.6.

Tabla 3.2.6. Significación en las diferencias en los modelos de regression de los parámetros considerados, en los terciles de velocidad.

	Elderly	**Young**
Cad Vs Vel	**	**
SL Vs Vel	**	**
SL Vs Cad	**	**

** = $p<0.01$

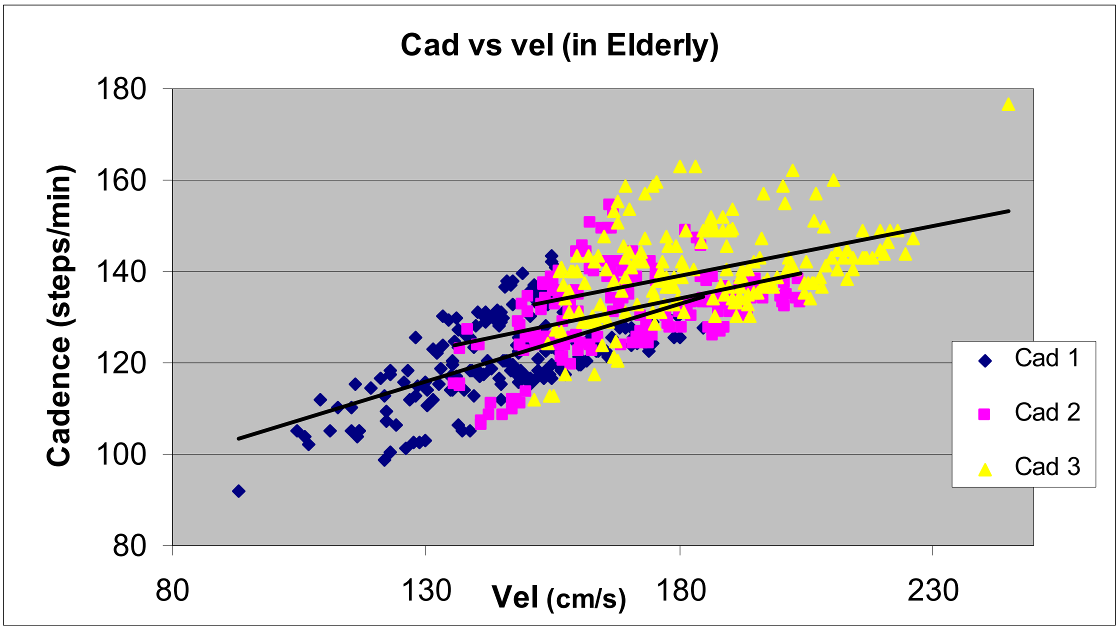

Figura 3.2.1. Gráfica de la frecuencia y la velocidad con sus correspondientes líneas de regression, en el test incremental de marcha, dividido en terciles de velocidad, en sujetos mayores.

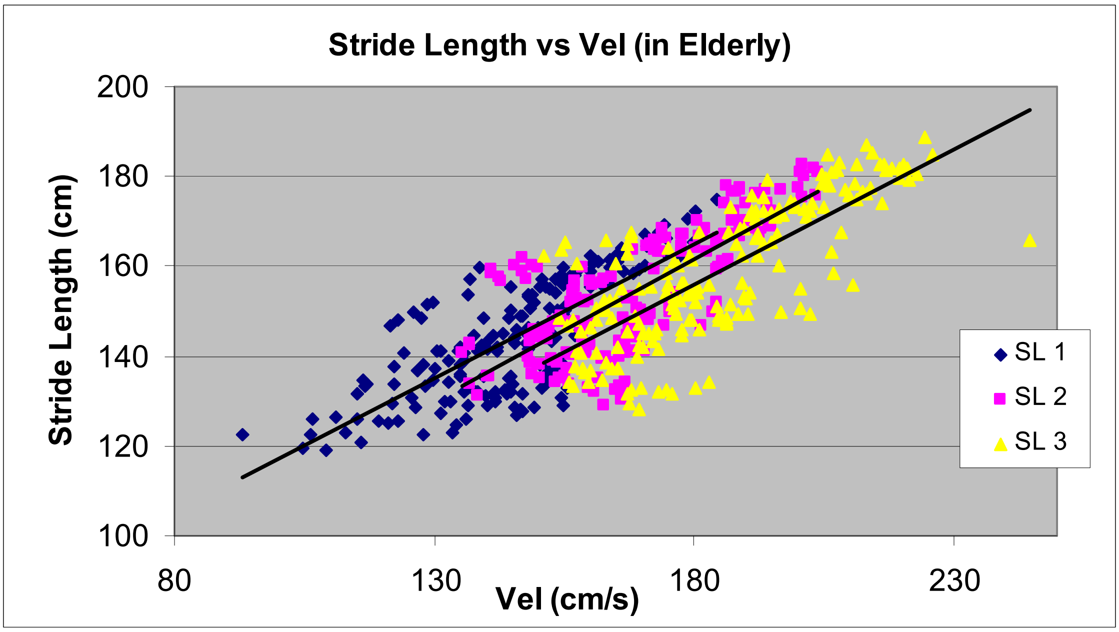

Figura 3.2.2. Gráfica de la longitud de zancada y la velocidad con sus correspondientes líneas de regression, en el test incremental de marcha, dividido en terciles de velocidad, en sujetos mayores.

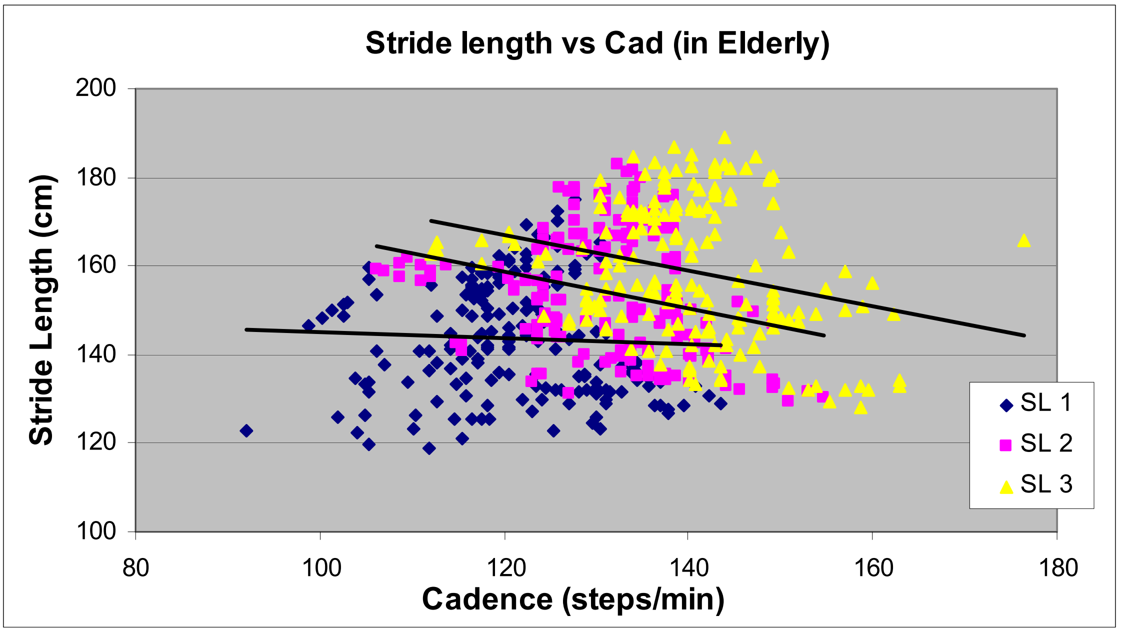

Figura 3.2.3. Gráfica de la longitude de zancada y la frecuencia con sus correspondientes líneas de regression, en el test incremental de marcha, dividido en terciles de velocidad, en sujetos mayores.

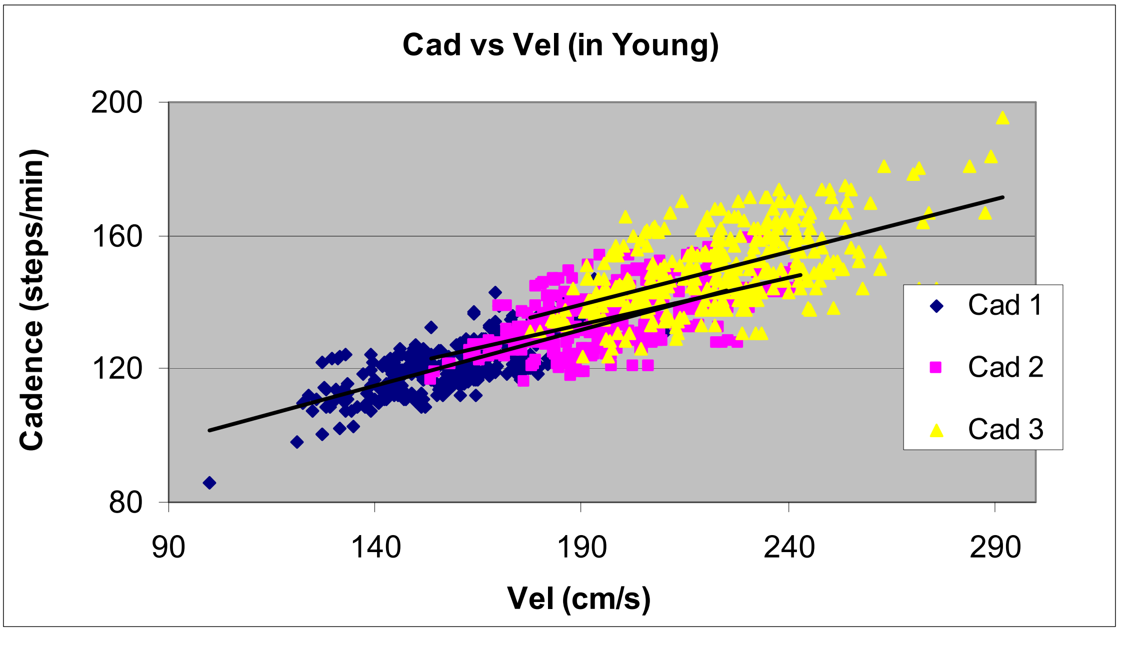

Figura 3.2.4. Gráfica de la frecuencia y la velocidad con sus correspondientes líneas de regression, en el test incremental de marcha, dividido en terciles de velocidad, en sujetos jóvenes.

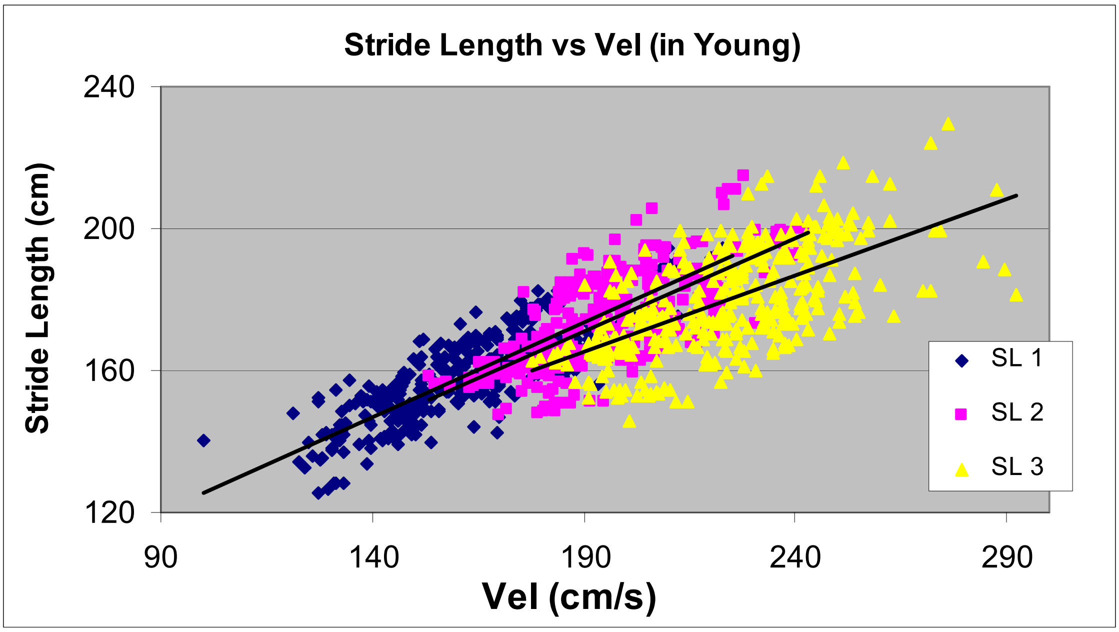

Figura 3.2.5. Gráfica de la longitud de zancada y la velocidad con sus correspondientes líneas de regression, en el test incremental de marcha, dividido en terciles de velocidad, en sujetos jóvenes.

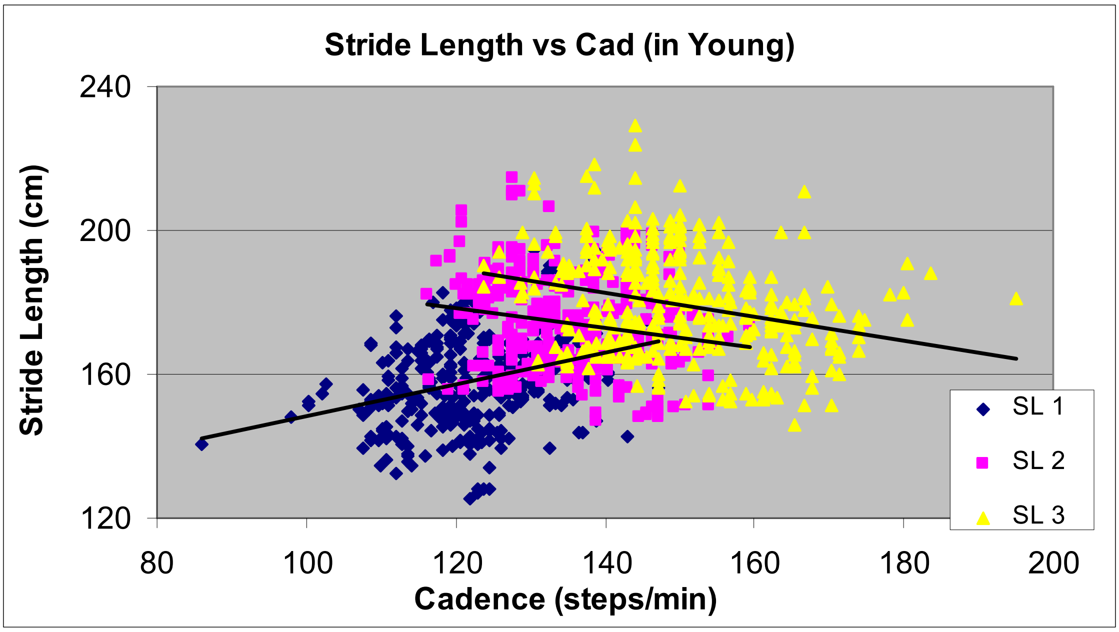

Figura 3.2.6. Gráfica de la longitude de zancada y la frecuencia con sus correspondientes líneas de regression, en el test incremental de marcha, dividido en terciles de velocidad, en sujetos jóvenes.

Estos gráficos evidencian que, en ambos grupos, la manera de modular los parámetros de marcha ha sido diferente para cada rango de velocidad, y estas diferencias se han mostrado muy significativas en cada pareja de parámetros considerada.

En vista de la amplia dispersión de datos evidenciado en los gráficos anteriores, en particular, en el rango relativo a la máxima velocidad, ha sido efectuado un análisis Anova de los parámetros espacio-temporales de marcha. Ambos grupos han mostrado en cada parámetro observado diferencias muy significativas entre las variantes en el interior de los grupos y entre los grupos. Para observar simplemente esta última circunstancia, la frecuencia de la zancada (que parece ser el parámetro que más influye en la velocidad de marcha) de los sujetos ancianos y de los más jóvenes, ha sido representada en las figuras 3.2.7. y 3.2.8. respectivamente.

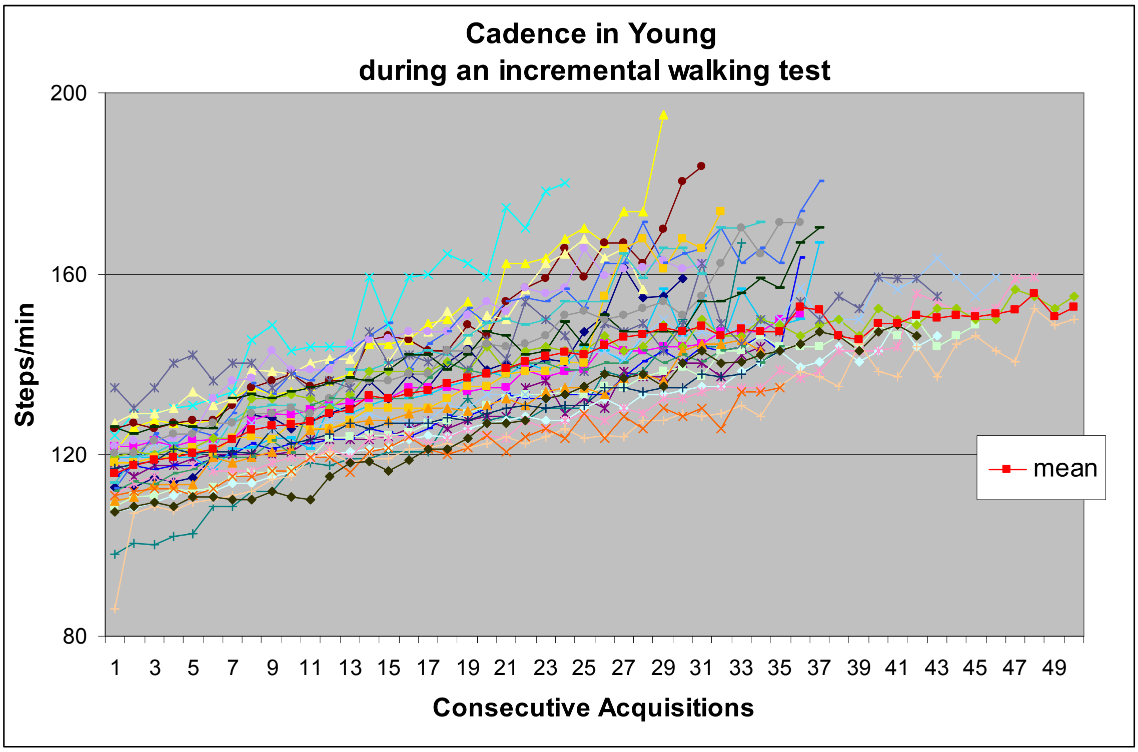

Figura 3.2.7. Gráfica de la frecuencia registrada durante la prueba incremental en el grupo de jóvenes. Se representan con puntos rojos los valores medios entre sujetos.

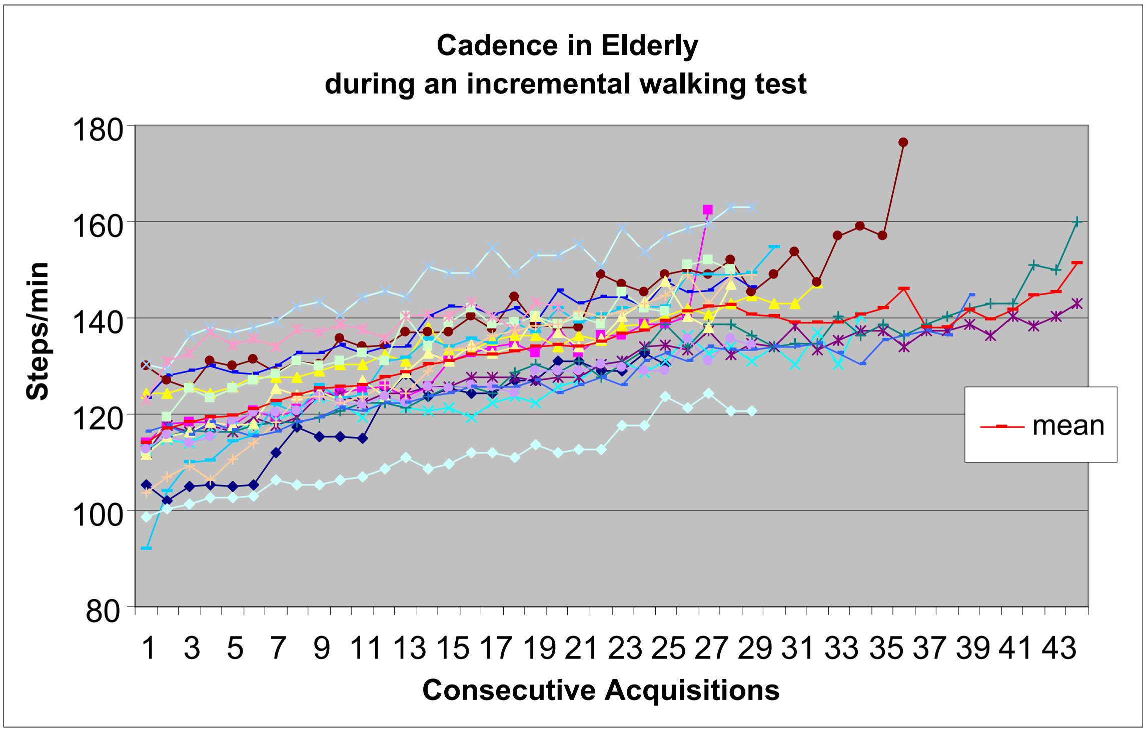

Figura 3.2.8. Gráfica de la frecuencia registrada durante la prueba incremental en el grupo de mayores. Se representan con puntos rojos los valores medios entre sujetos.

Se puede observar fácilmente que cada sujeto muestra una misma tendencia en el comportamiento de la frecuencia del paso durante el test incremental de marcha, pero cada uno se aleja diversamente de los valores medios de todo el grupo

3.3. Discusión

3.3.1. Cambios en los parámetros espacio-temporales de la marcha respecto a la edad y la velocidad

La locomoción humana es ciertamente la acción motora más analizada y argumento de una gran cantidad de bibliografía. Pero, tanto las restricciones de los laboratorios como de los protocolos experimentales, imponen valores a estos parámetros que hacen que la marcha no sea espontánea influenciando, probablemente, el análisis. Los protocolos más utilizados han implicado el caminar sobre una superficie limitada (Dusing et al. 2007), o caminar sobre un tapiz rodante (Owings et al. 2004; Li et al. 2005; Jordan et al. 2007). Además la velocidad de marcha más frecuentemente utilizada ha sido sólo la más confortable (Stansfield et al. 2006). En cambio, otras veces los protocolos han previsto caminar a distintas velocidades auto-seleccionadas por los sujetos pero con frecuencia se han limitado sólo tres (más confortable, más lenta, más rápida) (Grabiner et al. 2001; Moe-Nilssen et al. 2004; Hanlon et al. 2006; Mills et al. 2007) o incluso, cuando ha sido utilizado un tapiz rodante, la velocidad ha sido modificada a pasos fijos (Zijlstra et al. 2003; Li et al. 2005; van Hedel et al. 2006; England et al. 2007).

Para alcanzar los objetivos de este trabajo se ha buscado eliminar todo posible condicionamiento a la marcha natural de los sujetos. Los instrumentos utilizados y las dimensiones del circuito han permitido una marcha fluida y natural. Además, el protocolo utilizado nos ha permitido analizar los datos recogidos durante el desarrollo de una prestación motora percibida de la misma manera por cada sujeto (desde la más confortable hasta el máximo esfuerzo). Esto se ha hecho para evitar que una misma velocidad de marcha pueda requerir un desempeño diferente a personas con capacidades distintas. Por otra parte, el hecho de fraccionar los datos en tres rangos de velocidad y usar los valores medios de cada sujeto nos ha permitido no influenciar el análisis con las diferentes cantidades de datos recogidos para cada sujeto (el tiempo que cada sujeto necesitaba para ejecutar el test ha sido diverso, así como diversa ha sido la velocidad alcanzada durante las pruebas en relación a las capacidades del sujeto).

Todos los sujetos han aumentado la velocidad de marcha hasta el límite de su capacidad, alcanzando velocidades de marcha claramente superiores respecto a aquellas alcanzadas por otros grupos de sujetos reportados en literatura (Al-Obaidi et al. 2003; Zijlstra et al. 2003; Owings et al. 2004; England et al. 2007).

Tabla 3.3.1.1. Significación en las diferencias de los parámetros de marcha entre los terciles de la velocidad en sujetos jóvenes y mayores.

	Young			**Elderly**		
	1° Vs 2°	2° Vs 3°	3° Vs Max	1° Vs 2°	2° Vs 3°	3° Vs Max
vel	**	**	**	**	*	**
cad	**	**	**	**	**	**
S L	**	**0**	*	*	**0**	**0**
Norm vel	**	**	**	**	**	**
Norm cad	**	**	**	**	**0**	**
Norm S L	**	**0**	**	*	**0**	**0**

Observando los otros parámetros espacio-temporales de marcha (Tabla 3.3.1.1.), se ha revelado que, mientras la frecuencia del paso en ambos grupos ha mostrado diferencias altamente significativas entre los distintos rangos de velocidad, no ha sido lo mismo para la longitud de la zancada. Esto podría estar determinado por el hecho de que las personas ancianas, vista su reducida flexibilidad y movilidad articular (NHMRC 2004), saturan la longitud del paso anticipadamente si se comparan con los más jóvenes (de acuerdo con Hirasaki et al. 1999).

Muchas veces en literatura se han reportado valores de parámetros de marcha de los sujetos ancianos inferiores respecto a los de los jóvenes.

También en este estudio, en general, los ancianos han mostrado valores significativamente más bajos respecto a los más jóvenes (Tabla 3.2.3.), excepto para los valores normalizados de la longitud de la zancada; mientras que con respecto a la frecuencia del paso los ancianos han mostrado diferencias significativas respecto a los jóvenes sólo en los máximos rangos de velocidad.

Desde estos datos, pareciera deducirse que a la velocidad de marcha más confortable, los sujetos ancianos pueden mantener una capacidad de marcha similar a la de los sujetos más jóvenes (de acuerdo con Grabiner et al. 2001), y que sólo la prestación conducida más allá del límite “confortable”, determinado por las propias capacidades, podría permitir distinciones entre los sujetos jóvenes y los más ancianos.

Además, en literatura, se ha evidenciado que la variabilidad del paso puede ser influenciada por muchos factores entre los cuales: la combinación entre la longitud y la frecuencia del paso (Danion et al. 2003), el riesgo de una caída (Hausdorff et al. 1997), el miedo a una caída (Maki 1997), la variabilidad espacial (Sekya et al. 1997), la variabilidad temporal (Maruyama et al. 1992). En nuestro estudio, durante el test incremental de marcha, los coeficientes de variación de cada parámetro para ambos grupos se redujeron levemente con el aumento de la velocidad; mientras que a la velocidad de marcha más confortable, el grupo de ancianos ha mostrado coeficientes de variación levemente más bajos respecto al grupo más joven. Este último aspecto, difiere en algunos autores (Grabiner et al. 2001; Owings et al. 2004) que han observado coeficientes de variación mayores en sujetos ancianos comparados con sujetos más jóvenes, o cuando las personas han caminado a una velocidad mayor; pero otros autores como Li et al. (2005) han experimentado la misma situación que nosotros concluyendo que “el cuerpo humano es capaz de usar la variabilidad como un medio de exploración” y que “el aumento de las prestaciones motoras pide a nuestro sistema usar mayores recursos para completar la tarea primaria (por ejemplo, la marcha) limitando de hecho la capacidad de usar la variabilidad como medio de exploración”. Por el contrario, la desviación estándar de los mismos parámetros se ha revelado bastante amplia, aumentando más a las más altas velocidades de progresión. Por este hecho, ha sido efectuado un Análisis de Variación que como hemos visto antes, ha mostrado diferencias muy significativas de la variación en el interior de los grupos de sujetos respecto a la variación entre los grupos. Estos últimos resultados parecen indicar que todas las personas, jóvenes o ancianos, usan un modo similar para organizar los parámetros de la marcha, incluso si los valores de los mismos parámetros son distintos entre los sujetos, probablemente, en relación a las propias capacidades. Las figuras 3.2.7. y 3.2.8. muestran muy bien que la tendencia de los datos de cada sujeto ha sido la misma no obstante los mismos estén dispersos en un amplio rango.

3.3.2. Modulación de los parámetros de la marcha

La velocidad de la marcha es determinada por la simultánea modulación de la longitud y de la frecuencia de la zancada, por lo tanto, es fácil pensar que, para aumentar la velocidad de marcha, los hombres, adoptan el simultáneo aumento de los otros parámetros de marcha. Los resultados de este estudio han evidenciado como tal comportamiento parece ser un patrón de la marcha que se manifiesta hasta que la velocidad de marcha es percibida como confortable. En efecto, todos los sujetos han mostrado altos valores de correlación entre los parámetros de marcha sólo a la velocidad más confortable, mientras que en el aumento de la velocidad de marcha, en ambos grupos de sujetos, estos valores tienden claramente a disminuir. Algunas diferencias entre la modulación de los parámetros de marcha y entre los dos grupos de edad fueron de todas formas observadas. Sobre todo, la frecuencia de la zancada, que en ambos grupos, manteniendo valores de correlación con la velocidad más altos con respecto a la frecuencia de la zancada, parece el parámetro que más influencia los incrementos de la velocidad de marcha. Además, los sujetos ancianos han mostrado valores de correlación de los parámetros de marcha parecidos a aquellos de los jóvenes a las velocidades más confortables, pero una más rápida reducción de los mismos valores en el aumento de la velocidad de marcha. Además, esto parece confirmar que los sujetos ancianos mantienen la capacidad de reaccionar al incremento de las dificultades que el movimiento exige, hasta que el esfuerzo es percibido como confortable; límite éste que puede cambiar en relación a la edad fisiológica de los mismos. Además, los resultados del presente estudio han evidenciado que a los valores más altos de correlación media entre los parámetros de marcha, registrados a la velocidad más confortable, han correspondido los valores más bajos de desviación estándar entre los mismos parámetros; mientras, con el aumento de la velocidad de marcha, la media y la desviación estándar de los mismos valores son cambiados inversamente. Esto confirma que a la velocidad de marcha más confortable todas las personas regulan los parámetros de marcha en el mismo modo, pero cuándo el esfuerzo físico aumenta, las personas reaccionan diferentemente, en relación a sus propias capacidades.

Se debe destacar que todas las conclusiones referidas, hasta ahora, son sostenidas por el análisis de regresión jerárquica linear cuyos resultados se muestran en la tabla 3.2.6. mostrada anteriormente. Este análisis ha permitido evidenciar las diferencias en los modelos de regresión de los parámetros apareados, que resultaron muy significativos cuando han sido considerados en los rangos de velocidad. Además, este análisis se diferencia de otros análisis que se encuentran en literatura, dónde los datos son analizados en conjunto (Zijlstra et al. 2003; Brenière 2003; Stansfield et al. 2006). Se debe destacar que se podrían obtener diferentes valores de correlación analizando así los datos, pero este procedimiento podría ser engañoso (Tabla 3.3.2.1.).

Tabla 3.3.2.1: Coeficiente de correlación entre los parámetros espacio-temporales obtenidos en toda la muestra y en los terciles analizados de los sujetos mayores. Para cada subgrupo se han comparado los valores medios entre sujetos con los de toda la muestra.

ELDERLY	Corr. Coef. 1-33° percentile of Vel		Corr. Coef. 34-66° percentile of Vel		Corr. Coef. 67-100° percentile of Vel		Corr. Coef. 1-100° percentile of Vel
	mean values between subjects	whole sample	mean values between subjects	whole sample	mean values between subjects	whole sample	whole sample
Vel/Cad	0.94	0.45	0.82	0.45	0.81	0.35	0.71
Vel/SL	0.93	0.29	0.58	0.15	0.46	0.17	0.78
Cad/SL	0.77	-0.05	0.11	-0.27	0.00	-0.26	0.12
Vel/SuppBaseL	0.00	0.02	0.14	0.03	0.07	0.05	0.09
Vel/SuppBaseR	-0.01	0.00	0.12	0.04	0.12	0.08	0.10
Vel/DSuppTime	-0.78	-0.44	-0.62	-0.41	-0.65	-0.34	-0.82

Se debería reflexionar sobre esta cuestión, ya que muchas veces en literatura los datos son analizados de este modo, no considerando adecuadamente la variabilidad inter-sujetos.

5. CONCLUSIONES

El presente estudio ha demostrado que, jóvenes y ancianos, tienden a aumentar su velocidad de marcha aumentando tanto la longitud como la frecuencia de la zancada, con una correlación alta entre estos dos parámetros de marcha. Mientras la velocidad de marcha es percibida como confortable, las correlaciones entre los parámetros espacio-temporales de marcha resultan ser muy altos. Por otra parte, se ha observado que ulteriores aumentos de la velocidad de marcha, que parecen ser regulados mayormente por el aumento de la frecuencia de la zancada, determinan una neta reducción de los valores de correlación entre todos los sujetos. Esta característica motora ha sido evidenciada tanto en los sujetos jóvenes como en los ancianos, si bien se ha observado una amplia variabilidad inter-sujetos.

Los resultados del presente estudio parecen, por lo tanto, confirmar nuestra hipótesis según la cual la modulación de la longitud y de la frecuencia de la zancada, para sostener variaciones de la velocidad de marcha, puede constituir un modelo intrínseco de la marcha, que se hace aparente cuando el paso es confortable. Por esta razón, el modo que los sujetos adoptan para acelerar el paso depende de la capacidad motora de cada sujeto, y por lo tanto, del esfuerzo requerido. Aparece como evidente que éste ultimo aspecto puede ser la causa de una variabilidad inter-sujetos del fenómeno de la marcha muchas veces descrita en literatura. La misma variabilidad que, al no haber sido considerada oportunamente, puede haber llevado a conclusiones engañosas a aquellos autores que han tratado de resolver los problemas de la locomoción humana.

Con este trabajo se hace evidente, que si bien los estudios sobre la locomoción humana son ampliamente reseñados en literatura, incluso ahora, no tenemos un completo conocimiento del fenómeno. Ulteriores estudios serán seguramente necesarios para consolidar los resultados del presente trabajo, pero sólo a través de un acercamiento en el ámbito de la variabilidad podremos identificar todos los factores involucrados en la locomoción humana, y por lo tanto, describir las estrategias del acto locomotor.

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