Variations in spatiotemporal parameters in young and older women while walking at different speeds

Variaciones de los parámetros espaciotemporales en mujeres jóvenes y mayores al caminar a diferentes velocidades

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Abstract

The relationship between spatial-temporal parameters of walking have been widely described in literature although this is still unclear, particularly when changes in walking speed occurred. This study aims to investigate this relationship in healthy women of different ages, while walking at different speeds. Two groups of healthy women (25 young and 22 elderly) walked at "comfortable" and "fast" speeds. Stride length and frequency, plus walking speed data were recorded. Their relationship was assessed using bivariate regression analysis and Pearson's correlation. Both groups showed that increasing velocity, increased significantly stride length and frequency, walking comfortably. Nevertheless, differences between groups were highlighted during fast walking. The elderly maintains a similar walking pattern though reducing the correlation coefficient between the parameters. While the younger shows significant correlation only between stride frequency and velocity. Concerning stride length and frequency relationship, both groups exhibit different behaviors between the observed walking speeds. In conclusion, these results suggest that younger and older women increase walking speed using a pattern only whilst the effort is perceived as comfortable. Identifying this breaking point in the motor patterns used could help to identify early possible frailties in older people as well as assess the residual state of their functional capacities.

Key words*:* Walking, gait analysis, aging, stride parameters, gait strategies.

Resumen

La relación entre los parámetros espacio-temporales de la marcha ha sido ampliamente descrita en la literatura, aunque aún no está clara, sobre todo cuando se producen cambios en la velocidad de la marcha. Este estudio tiene como objetivo investigar esta relación en mujeres sanas de diferentes edades, mientras caminan a diferentes velocidades. Dos grupos de mujeres (25 jóvenes y 22 mayores) han caminado a velocidades "cómodas" y "rápidas". Se registraron la longitud y la frecuencia de la zancada, y la velocidad de la marcha. Su relación se evaluó mediante análisis de regresión bivariado y correlación de Pearson. Ambos grupos, caminando cómodamente, mostraron que, al aumentar la velocidad, aumentó significativamente la longitud y frecuencia de la zancada. Sin embargo, las diferencias entre los grupos se destacaron durante la marcha rápida. El anciano mantiene un patrón de marcha similar, aunque reduce la correlación entre los parámetros. Los más jóvenes muestran una correlación significativa solo entre la frecuencia de zancada y la velocidad. En cuanto a la relación entre la longitud y la frecuencia de zancada, ambos grupos exhiben comportamientos diferentes entre las velocidades de caminata observadas. En conclusión, estos resultados sugieren que las mujeres jóvenes y mayores aumentan la velocidad de la marcha utilizando un patrón únicamente mientras el esfuerzo se percibe como cómodo. Identificar este punto de quiebre en los patrones motores utilizados podría ayudar a identificar tempranamente posibles fragilidades en las personas mayores, así como a evaluar el estado residual de sus capacidades funcionales.

Palabras clave: Andar, análisis de la marcha, envejecimiento, parámetros de marcha humana, estrategias de marcha.

Introduction

Walking speed and the two factors that determine it, stride length and stride frequency, are used to characterise walking both in able bodied and pathological populations, as well as in a specific individual (Kressig et al., 2004; Montes-Alguacil et al., 2019). In addition, walking speed, as a product of stride length and stride frequency, could be modified by varying either or both of these parameters. For this reason, in order to increase the velocity, subjects normally increase both parameters, but the relative weight given to each of them varies according to age, sex and pathology.

Although spatial-temporal parameters have been widely described in literature, conclusions are not always consistent, particularly with regards to differences between younger and older people (Hurt et al., 2010; Owings & Grabiner, 2004). Some authors highlighted the reduced speed of elderly gait and explained it as being associated with the reduced stride length (Elble et al., 1991; Hageman & Blanke, 1986), while others concluded that there were no significant differences between younger and elderly men in stride length, as well as in velocity (Blanke & Hageman, 1989).

These above-mentioned discrepancies could be caused by the fact that during walking, the variability, within subjects, of the spatial-temporal parameters increases with increasing speed (Jordan et al., 2007; Magnani et al., 2019), age or disease (Hausdorff et al., 1997). This means that there are many factors that can affect the way of walking. As highlighted in literature (Almarwani et al., 2016), gait variability is a marker of gait performance, showing that younger adults are more stable and fluctuate less over time compared to older adults. Moreover, in some studies (Brenière, 2003; Danion et al., 2003), characterising the relationship between temporal-spatial parameters at different walking speeds, data was analysed not accounting for the fact that subjects could change their way of modulating stride frequency and stride length, according to their own natural way. Furthermore, the setting protocols could affect the subjects' way of walking.

Several studies have investigated the relationship between temporal-spatial parameters during increasing walking speeds. However, few studies investigated if this relationship depended on the walking speed, that is, if it different at higher than at lower speeds (Jordan et al., 2007). These changes were highlighted by differences found between elderly and younger subjects when they were asked to change their walking speed, reaching their maximum velocity (Cherubini et al., 2005), or when a change in gait strategy at very slow walking speed was found (Smith & Lemaire, 2018). These observations allowed us to hypothesise that during walking, the increase in velocity may be supported by different ways to regulate stride length and stride frequency.

Therefore, the main objective of this study was to analyze the relationship between temporal-spatial parameters of gait in able-bodied women while walking at two self-selected speeds: comfortable and maximum speeds. Thus, we firstly were aimed at testing whether the strategy of modulating stride length and frequency depended on the walking speed. Secondly, we asked if this strategic changes in modulation different between younger and older women.

The new evidence that this study will show could open a new debate regarding the characterisation of temporal-spatial walking parameters which, despite ample research, still presents unknown aspects. Furthermore, if there is a breaking point in the motor patterns of human walking, being able to detect this point would allow the early identification of any frailty of elderly people through a simple walking test.

Materials and Methods

Participants

Walking stride parameters were analyzed in two groups of healthy older and younger adult females, n = 22 (71.4±3.9 years old) and n = 25 (23.6±4.2 years old) respectively. The volunteer subjects signed an informed written consent before participating in the study. Younger people were recruited from the students of the Rome University (between 19 and 28 years old), while the older people were recruited from the participants in activities directed at elderly people (+65 years old) organized by municipality of Rome.

Anthropometric parameters of participants were shown in table (table 1).

Table 1. Descriptive analysis of the subjects participating in the study

	Older women (n.22)				Younger women (n.25)			
	Age (years)	Height (m)	Leg Length (m)	Body mass (kg)	Age (years)	Height (m)	Leg Length (m)	Body mass (kg)
Mean	71.4	1.55	0.88	64.9	23.6	1.68	0.93	62.0
SD	3.9	0.06	0.04	8.0	4.2	0.08	0.05	11.4

SD = Standard Deviation.

Each subject has had a medical examination certifying their health status: only those having no history of vestibular disease or other disorders that would affect their locomotor performance were selected. Beside, all those who were affected by illness, conditioning the complete functionality of their way of walking, were also excluded. The study was approved by the ethics committee of the University of Rome "Foro Italico" and it complied with the ethical standards of the World Medical Association Declaration of Helsinki.

Material and testing

The instrumented mat

Contact between foot and ground was detected by using a purposely built 4 m long instrumented mat, as in Pecoraro et al. (2006). Seven millimeters wide adhesive copper strips were laid longitudinally with a space of 3 mm between them on the pathway where the subjects walked. These strips were alternately wired to two independent circuits, one for each foot. When a subject's foot, wearing a sock made of a conductive textile, came in contact with the ground, two adjacent strips were short-circuited and a signal was generated. This signal was fed to the A/D converter of the VICON® system illustrated later and synchronized with movement data. The mat's length (4 m) 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 placed under the mat, during a set of walking trials. Considering the fact that the mat allows us to measure more than one stride, it has proven to be a suitable tool for the purpose of this study. The timing of the foot's initial contact with the ground allowed the calculation of stride duration (T).

The stereophotogrammetric system

The stride length was determined using a nine camera VICON 612® system. It allows the reconstruction of the 3-D instantaneous position of spherical retro-reflective markers (14 mm in diameter) with an accuracy within 2 mm, as assessed performing the spot-check described in Della Croce and Cappozzo (2000). Cameras were located so that the relevant measurement volume was 6x2x2 m3. Marker positions were captured at a frequency of 120 samples per second. A dynamic calibration approach was used to calibrate the system.

Two markers were positioned on an elastic band that the subjects wore over their foreheads. The trajectories of these markers were used to define a mean axis of progression.

A further marker was positioned on the subjects' skin over the spinous process of the seventh cervical vertebra (C7). In this respect, according to Saunders's definition of human walking (Saunders et al., 1953), stride length is defined as the distance covered by any point of the subject's body during a walking cycle normally identified by two successive heel strikes of the same foot. The above-mentioned C7 marker was chosen for practical reasons and its reconstructed trajectory, along the mean axis of progression together with the recorded foot contact timing, were used to measure stride length.

Experimental Protocol

The participating subjects were all examined during the same week and during the morning to avoid any sort of physical fatigue. Moreover, with the aim to avoid any influence due to laboratory protocols, we tried to analyse the phenomenon in the most natural possible way. The subjects were asked to walk at two different speeds verbally defined as: "Walk at your natural speed" (comfortable) and "Walk as fast as you can" (fast).

Subjects walked an 8 m distance: starting 2 m before and stopping 2 m after the mat surface. They were instructed to look at a visual target located at the end of the pathway. For each task, three trials were carried out and for each trial, data regarding two subsequent strides was acquired. The walking distance was not such as to determine a physical tiredness that could influence the following test. Therefore, the recovery time between the tests, aproximatly one minute, was only necessary to reset the measurement system.

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

Stride length (SL);

Stride duration (T);

Stride frequency (SF): 1/T;

Mean walking speed (V): SL/T.

In many studies, concerning temporal-distance parameters related to walking speed, the parameters were not normalized (Crowninshield et al., 1978; Grieve & Gear, 1966; van der Linden, et al., 2002). However, in the literature, this normalisation finds more specific application in studies on growing children. To avoid the introduction of differences in data, for differences in size between the two subject groups, the parameters were normalized according to the literature (Hof, 1996; Stansfield et al., 2006; Vaughan et al., 2003), utilizing dimensionless numbers as follows:

NSL = SL/Ll (where Ll is the subject's leg length);

NSF = SF/(g/Ll)1/2 (where g is the gravitational acceleration);

NV = V/(gxLl)1/2 (Hof & Zijlstra, 1997).

The data for each subject was averaged across the three trials.

Table 2. Descriptive analysis of walking stride parameters in the older (n = 22) and young subjects (n = 25) during most comfortable and fast walking

	Comfortable walking			Fast walking			
	Older Mean (*SD*) (min; max)	Young Mean (*SD*) (min; max)	*p*	Older Mean (*SD*) (min; max)	Young Mean (*SD*) (min; max)	*p*	*p* O vs Y diff.
V (m/s)	1.04 (0.15) (0.72; 1.27)	1.31 (0.25) (0.93; 2.20)	< .001	1.64 (0.18) (1.31; 2.08)	2.30 (0.26) (1.81; 2.75)	< .001	< .001
SL (m)	1.09 (0.16) (.65; 1.34)	1.38 (0.13) (1.18; 1.69)	< .001	1.26 (0.14) (0.96; 1.45)	1.66 (0.15) (1.40; 1.97)	< .001	.01
SF (stride/s)	0.96 (0.13) (0.76; 1.41)	0.95 (0.11) (0.72; 1.30)	.47	1.32 (0.13) (1.14; 1.55)	1.39 (0.22) (1.07; 1.85)	.08	.07

The last column shows significance of older vs young differences in the values recorded at the two way of walking. *SD* = Standard Deviation; V = Mean walking speed; SL = Stride length; SF = Stride frequency.

Statistical analysis

Means, standard deviations and normality (Kolgomorov-Smirnov's test) and homogeneity (Levenes's test) were used as descriptive statistics. The Pearson's correlation coefficient was calculated to quantify the relationship between the variables of interest, while Student's t-test were used to determine the significance of differences between their mean values. The connection between the gait spatial-temporal parameters was analysed using bivariate regression analysis. Stride length and stride frequency versus walking speed were analysed for both groups. The significance level was set up to .05. All statistical analysis was done using SPSS for Windows, V19.0 (SPSS Inc., USA).

Results

Some differences in the temporal-spatial parameters of gait between young and older people, have been highlighted both at most comfortable and at maximum walking speeds. The older subjects showed lower values for walking speed and stride length than the younger participants both in comfortable ($p < .001$) and in fast ($p < .001$) walking speeds (Table 2).

Regarding stride frequency, the older and younger subjects showed very similar values for both comfortable ($p = .47$) and fast ($p = .08$) walking speeds. Moreover, we can observe that the younger and the elderly groups showed highly significant differences in variation of the two walking ways. These differences were observed in speed ($p < .001$) and stride length ($p = .01$), but not in stride frequency ($p > .07$).

Table 3. Descriptive analysis of normalized walking stride parameters in the older (n = 22) and young subjects (n = 25) during most comfortable and fast walking

	Comfortable walking			Fast walking			
	Older Mean (SD)	Young Mean (SD)	*p*	Older Mean (SD)	Young Mean (SD)	*p*	*p* O vs Y diff.
NV	0.35 (.05)	0.44 (0.08)	< .001	0.56 (0.06)	0.76 (0.09)	< .001	< .001
NSL	1.24 (0.16)	1.48 (0.14)	< .001	1.44 (0.14)	1.78 (0.12)	< .001	.02
NSF	0.29 (0.04)	0.29 (0.03)	.25	0.39 (0.04)	0.43 (0.06)	< .05	.05

The last column shows significance of older vs young differences in the values recorded at the two way of walking. *SD* = Standard Deviation; NV = Normalized mean walking speed; NSL = Normalized stride length; NSF = Normalized stride frequency.

As indicated before, following the standards in this literature, we run statistical tests on normalization. The same pattern of significant results was observed for normalized data (Table 3). Thus, the older subjects showed significant lower values than those of the younger group for the walking velocity and the length of the stride both during comfortable ($p < .001$ and $p < .001$, respectively) and fast ($p < .001$ and $p < .001$, respectively) walking speed.

Furthermore, for the stride frequency, significant differences were observed between older and younger groups just during the maximal walking speed ($p < .05$), while no significant differences were found while walking comfortably.

Bivariate linear regression analyses for normalized data on walking speed and temporal-spatial parameters (Figure 1) indicated that at a comfortable walking speed, both older and younger groups sustain the higher velocities by increasing both stride length ($r = .85$; $p < .001$ and $r = .87$; $p < .001$ respectively) and frequency ($r = .75$; $p < .001$ and $r = .94$; $p < .001$ respectively). However, during fast walking, the older group showed the same way of modulating walking speed, by increasing stride frequency ($r = .51$; $p = .01$) and length ($r = .48$; $p = .02$), but the younger subjects, modulated the walking speed by increasing the stride frequencies ($r = .9$; $p < .001$) and not the stride length ($r = -.2$; $p = .4$).

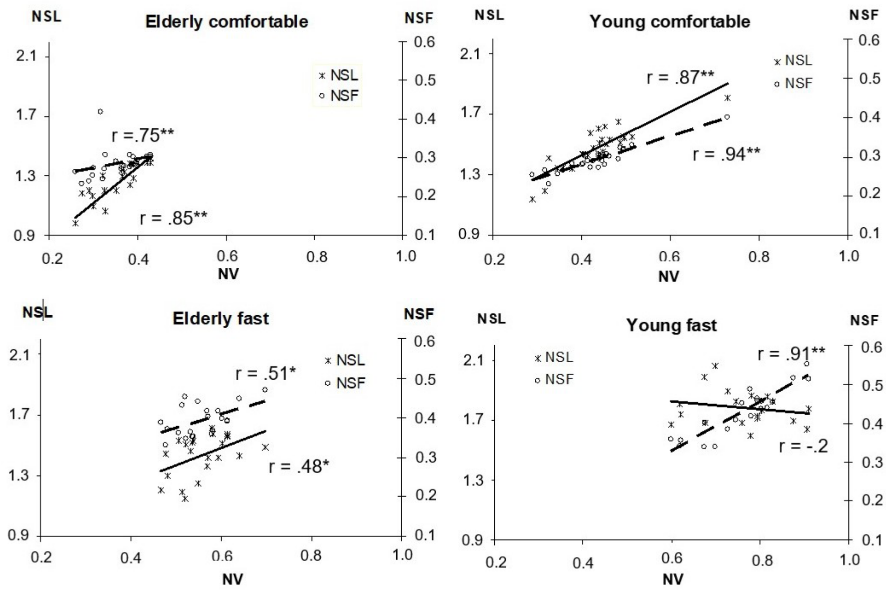

Figure 1. Regression lines and the relative Pearson's product moment between normalized stride length (NSL), frequency (NSF) and the dimensionless walking speed (NV) in Young and Older Subjects at comfortable and fast speed.

** = $p < .001$ * = $p < .05$

The regression analyses conducted between stride length and stride frequency indicated that both groups showed a different modulation of normalized stride parameters in the two different ways of walking (Figures 2 and 3). Indeed, at comfortable speed, the younger group, but not older, increased stride length significantly while increasing stride frequency ($p < .01$; $p = .17$ respectively). Conversely, at fast speed, higher values of stride length are associated to lower values of stride frequency for younger ($p < .01$) and older ($p < .05$).

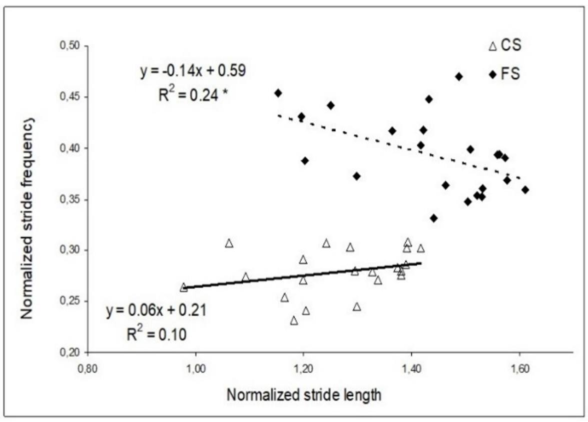

Figure 2. Older Group: Normalized stride length Vs Normalized stride frequency in comfortable and fast speed

* = p < .05

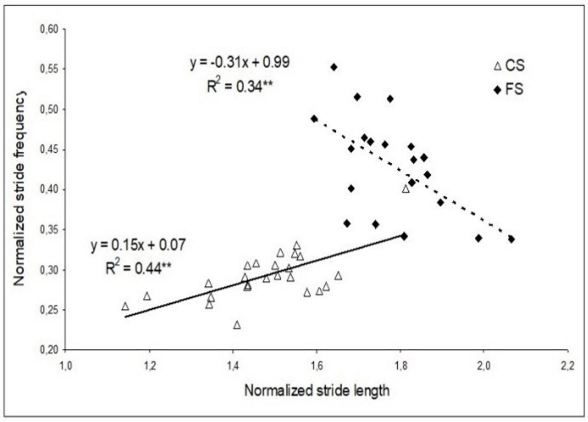

Figure 3. Young Group: Normalized stride length Vs Normalized stride frequency in comfortable and fast speed.

** = $p < .01$

Finally, we tested whether these correlation coefficients differed between groups and for the two ways of walking. This analysis indicated that regression slopes differently for comfortable than for fast speed for both groups (z = 2.78 and p = .005; z = 2.27 and p < .002 respectively for younger and older people). Moreover, differences between groups were observed at maximum (z = 2.283 and p = .011), but not at comfortable (z = 1.519 and p = .128) walking.

Discussion

The aim of this current study was analysed the relationship between temporal-spatial parameters of gait in able-bodied women while walking at two self-selected speeds: comfortable and maximum speeds. Our main outcome suggests that, in addition to spatio-temporal parameters largely reported in literature (Danion et al., 2003; Herssens et al., 2018), it is important to consider both age and speed comfort to obtain a more complete account for walking speed features. Indeed, we have shown that at a comfortable speed, the overall behaviour of the two groups can be considered similar, increasing their walking speed by increasing both parameters; whereas during fast walking, the differences between older and younger subjects became more evident. The olders maintained the same tendency during a faster walking speed than during a more comfortable one, but the correlation values, as shown in the figure1, between the parameters are reduced. This means that the older subjects, although they continue to support faster walking increasing both stride length and frequency significantly, they do this by increasing the variability within the group. Differently, the younger subjects have shown to achieve maximum walking speed using the stride frequency only, maintaining high correlation values between these parameters (r = .9). They showed no correlation between stride length and velocity at the maximum speed.

The results of the present work are consistent with the results of Hirasaki et al. (1999). and partially differ from Danion et al. (2003). The latter reported that "changes in speed during free walking, result more from a change in stride length than in frequency" and concluded that "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". The differences from Danion's conclusions are probably due to a lower maximum walking speed performed during their evaluations (1.77 vs ours 2.3 m/s). Indeed, observing our data, it is at the highest walking speeds that both groups have highlighted changes in walking strategies. However, the speed range used by Hirasaki et al. (1999), reaches a maximum walking speed very similar to ours (2.2 m/s).

Our data suggests that both groups coordinate the movement of walking with both stride length and frequency to increase their speed, while this is within a range perceived as comfortable. Beyond this threshold, they can increase their velocity, but each one in a different way, which varies between subjects, probably due to their neuro-motor skills. Indeed, these differences between subjects can be attributed only to their different morpho-functional characteristics. This increase in gait variability in older people is an aspect that has already been widely highlighted in the literature (Almarwani et al., 2016; Osoba et al., 2019; Savica et al., 2016).

On the other hand, the younger subjects, at their fastest speed, showed no significant correlation of stride length with walking speed. In concordance with Hirasaki et al. (1999), this is probably because it is easier for them, due to their age, to reach maximum amplitude in leg movements, before reaching the maximum frequency of the same movements. Indeed, it is a well known fact that aging easily leads to functional deteriorations, which causes a reduction in the amplitude of movements (Gamwell et al., 2022).

The same process of natural aging, which determines a reduced efficiency in the vital functions of older people, leads to a general decrease in motor performance and consequently, to a lower threshold of walking speed according to Malatesta et al. (2004). Therefore, their performance can be based on their subjective residual functional capabilities that are related to their health and physical efficiency. On the other hand, if the subject's capacity influences his motor performance, the motor demand also influences the subject's performance (Craig et al., 2019). The results of this study highlighted that the way younger and older subjects combine stride length and cadence to increase walking speed strictly depends on the demand of motor tasks they have to perform. Both groups showed clear differences in length and cadence combination, between comfortable and fast walking. Our findings are consistent with Egertone's results about stride length–cadence relationship (Egerton et al., 2011). Therefore, this seems to support the thesis that different subjects can support differently the efforts required during walking at higher intensity, modulating the stride parameters according to one's capability. These results are consistent with literature in which it is highlighted that older people adjusted the walking parameters differently, "depending on which type of balance demand was encountered" (Shkuratova et al., 2004). Furthermore, the greater variability in coordinating the length and frequency of the stride during walking could be functional and not just random variations interfering with normal functioning (Hausdorff et al., 1997). From the results of this study, it seems that the modulation of the spatial-temporal parameters of gait to increase walking speed could be considered an intrinsic gait pattern used by individuals during more comfortable walking, which will change on an individual level as the effort required increases. If so, the gait analysis carried out on older people could allow to highlight possible fragility or possible onset of pathological phenomena which, if detected prematurely, would allow more effective early interventions. In other words, the analysis of the walking of elderly subjects, as observed by Ricciardi et al. (2019) to classify subjects with parkinson's, could be considered a useful tool for an early diagnosis of onset pathologies that can affect daily life. Moreover, according to Kressig et al. (2004), the implications of these findings focus on the need to extend the classification system in older adults beyond age alone. This could bring about more meaningful and better-focussed categories based on their functional status in daily activities.

Several limitations of this study must be highlighted. First, a limit to this study was the reduced walking distance available in the laboratory. This limit was avoided by using the central part of the walkway to avoid data contamination due to the acceleration and deceleration of the walking phases. Another limitation concerns the composition of the sample which is made up exclusively of women. This does not allow to generalize our results also to the male gender of the population. Finally, a limitation could be considered that of having used free walking to carry out the tests, given that the most common approach to control for walking speed is through treadmill walking. Actually, this was done to minimize any influence on the most natural form of walking of each subject. Indeed, the treadmill acts as an external cue, which may decrease gait variability (Dingwell et al., 2001).

In this study temporal and spatial parameters of human gait were analysed all together while in most studies, they have been treated separately (Goldie et al., 2001; Maruyama & Nagasaki, 1992), but doing it this way, it is possible to fail to understand the whole phenomenon of human gait.

Conclusions

In conclusion, analysing the relationship between the temporal-spatial walking parameters separately for the two different walking tasks, allowed us to highlight some differences between younger and older women in the stride length/frequency modulation. All subjects, walking comfortably, showed a similar movement pattern, increasing their walking speed by increasing significantly both parameters, stride length and frequency. While, by walking faster, both groups have shown that they use a different walking strategy, compared to the one used in the most comfortable walk, and above all, to do it in a completely different way. As stated above, these differences could be attributed to a different level of motor capacity between the groups and within them.

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