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Original paper

The impact of changes in gait speed and step frequency on the extent of the center of mass displacements

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Center of mass (COM) trajectory plays a crucial role in the analysis of human body movements. This research aimed at studying vertical and transverse COM displacements during gait on a treadmill at a given velocity and step frequency.

Locomotion study was accomplished using: Vicon 250, Cardionics Treadmill 3113 and metronome Korg Ma-30. The data achieved for 12 women and 15 men aged 21–22 revealed similarity in vertical COM oscillations in both groups.

Lateral COM displacements (L_{COM}) were slightly higher in men than in women and they showed tendency to decrease as gait velocity increased. During natural locomotion there was an increasing trend as walking speed increased. At a given velocity of locomotion L_{COM} were decreasing as step frequency increased.

The only astonishing thing was that the biggest changes of vertical COM oscillations (V_{COM}) were noticed at the fastest walking speed (6 km/h). It seems that so large decrease in V_{COM} during walking with high velocity and increased step cadency is a consequence of considerable shortening of the movement cycles and performing time of one step.

Key words: *gait analysis, center of mass (COM) displacements, step frequency*

1. Introduction

Kinematic and dynamic studies of human locomotion have a long tradition. Gait occupies a privileged position in the researchers' field of interests [1], [2]. An additional aspect that expands a group of scientists dealing with this issue is the influence of the previous injuries, diseases [3] and ageing processes [4].

Due to more advanced methods of measurement it was possible to accomplish the movement recording of particular body segments during gait [5], [6], the registration of ground reaction forces [7], and the assessment of the muscles group forces [8]. Besides, during body transition one can study bioelectrical muscles activity [9] or energy expenditure of this form of locomotion [10], [11]. These issues are addressed not only in relation to physiological gait [12], but also different varieties of pathological gait [3], [13]. Numerous investigations on gait biomechanics sometimes seem to encourage researchers to take up some minor problems of human locomotion like biomechanical study of backward gait and its application to physiotherapy [14].

To describe any movement of the body, the COM trajectory is of importance [15], [16]. The data referring to location and transformation of this point can be used to determine kinematic [17] and dynamic parameters of gait [18], as well as to cope with the problems of balance during locomotion [19], [20]. Considering individual variability of human body structure and complexity of locomotion it can be concluded that description of COM behaviours during walking is a complex task and basically impossible to implement without adequate and reasonably complex measuring apparatus. As mentioned before, the complexity of methodical research can lead to significant differences in the measurement results [21], [22].

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The purpose of this paper was to determine the vertical and transverse COM displacements in women and men during gait on the treadmill at a given velocity and step frequency.

2. Methods

12 women and 15 men, aged 21–22, volunteered to participate in the studies carried out in the Biomechanics Laboratory of the University School of Physical Education in Kraków. The inclusion criteria aimed at selecting only the subjects without any previous injuries referring to passive or active movement apparatus. Morphological data of the participants were as follows ($\bar{x}$ ±SD): body height 1.72 ±0.04 m (women – W) and 1.81 ±0.04 m (men – M), body mass 58.01 ±7.31 kg and 78.7 ±8.42 kg, respectively.

Fig. 1. The manner of carrying out the study:
1, 2 – cameras, 3 – treadmill, 4 – subject during registration session
(photo: G. Latocha)

Locomotion study was accomplished with the following equipment: Vicon 250, Cardionics Treadmill 3113 and metronome Korg Ma-30. The participants, dressed solely in swimming suits and comfortable sports shoes, were instructed to walk on the treadmill set in the cameras field (created by 5 cameras). Each camera was working with the frequency of 125 Hz. The schema of measuring stand is shown in figure 1.

Every time there were recorded 15–20 gait cycles at three different velocities of 4, 5 and 6 km/h. At each variant of speed the participants used gait with natural (*n*), self-selected step cadency, which increased by 5 and 10% (n + 5%, n + 10%) and decreased in the same way (n – 5%, n – 10%). Step frequency, different than natural, was constrained by the sound signal emitted by a metronome. Natural step frequency at a given velocity was shown in the table.

Table. Natural step frequency on the treadmill at given velocity for women (W) and men (M) (mean ± SD)

	4 km/h		5 km/h		6 km/h	
	steps/min	Hz	steps/min	Hz	steps/min	Hz
W	109 ±1.7	1.82	115 ±7.4	1.92	122 ±4.9	2.03
M	113 ±8.4	1.88	118 ±5.9	1.97	127 ±7.6	2.12

In our research, whole body was covered with the reflective markers (25 mm in diameter) placed on the person's skin at 39 anthropometric points in a manner consistent with the methodology of Golem model, developed by the creators of the Vicon system. This model consists of 15 interconnected segments.

Prior to data collection, the corresponding anthropometric parameters of body build were measured and introduced to a computer

On the basis of the data obtained there were determined individual vertical (V_{COM}) and lateral (L_{COM}) values of COM displacements during gait: expressed as the velocity (v) and step frequency (f) functions and mean values for women and men. The values of each variable were normalized to a percentage of a gait cycle (GC), assuming that 100% mean a range within successive contacts of ipsilateral foot with the ground.

3. Results

Figure 2 shows individual graph of COM position in sagittal plane (V_{COM}) in one gait cycle. The function, in terms of quality, is typical of all the women and men examined. As was noticed, four local extreme values could be measured: maximum in 30% and 80% of GC being relevant to that period of gait, when leading limb is loaded, but knee joint is extended. However, minimum was in 5% and 55% of GC that is appropriate to successive double support phases.

Figure 3 illustrates lateral COM displacements (L_{COM}) of one person during gait on the treadmill. Like in figure 1, the graph presented is typical of all the subjects. Both, the highest and lowest, recorded values (about 30% and 80% GC) are relevant to subsequent entirely loaded feet resulting from body weight bearing by left and right lower extremities.

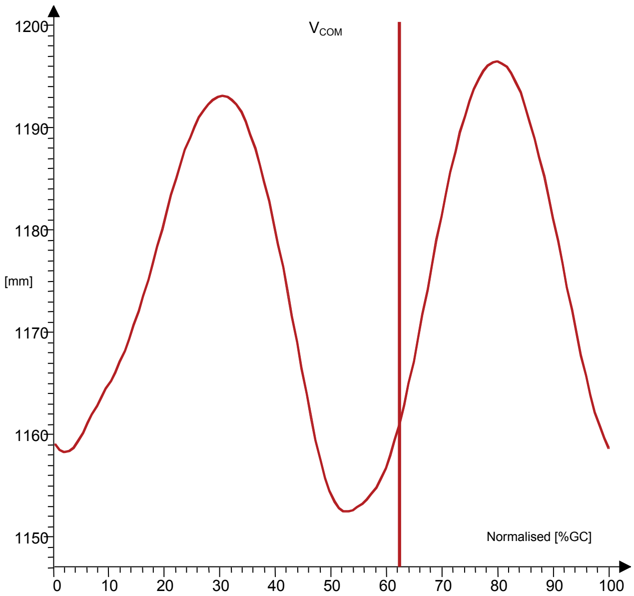

Fig. 2. An example of trajectory of vertical COM oscillations (V_{COM}) during gait (vertical line – the end of stance phase)

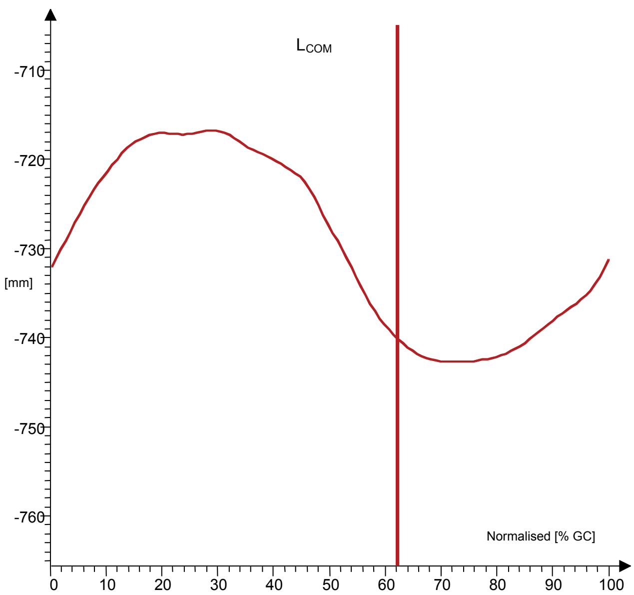

Fig. 3. An example of trajectory of lateral COM displacements (L_{COM}) during gait (vertical line – the end of stance phase)

Vertical COM mean values in women and men during natural gait are given in figure 4. They increased as velocity increased. Increasing the speed from 4 to 6 km/h resulted in the increase of vertical COM displacements in women by approximately 18 mm; the mentioned growth in the group of men was slightly lower and amounted to 14 mm. There can also be noticed some differences in the changes of oscillations in both sexes; at a speed of 4 km/h vertical oscillations are larger in males, at a speed of 5 km/h are almost identical in both sexes and at a speed of 6 km/h – slightly higher in women.

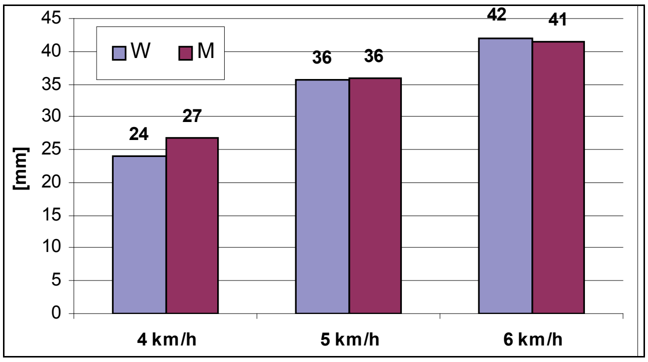

Fig. 4. Mean values of V_{COM} (mm) during gait with natural step frequency in women and men

Figure 5 represents lateral COM displacements of women and men during walking. In both sexes, there was noticed a decrease in the oscillations of this movement accompanied by increasing locomotion speed, whereas this tendency was more visible in women. L_{COM} values in men ranged between 24 and 32 mm and were pursued in the case of each gait speeds greater than in women.

Comparing the values shown in tables 4 and 5 we can see that in the case of velocity increase from 5 km/h to 6 km/h, lateral COM oscillations in men increase, while in women they decrease.

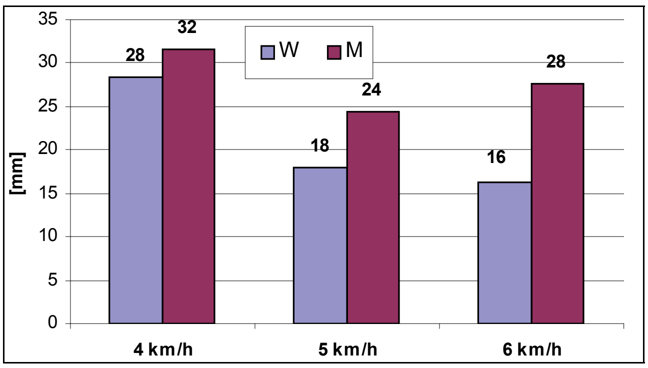

Fig. 5. Mean values of L_{COM} (mm) during gait with natural step frequency in women and men

The changes of vertical COM oscillations in men in each gait variant in the current study are shown in figure 6. The highest value (50 mm) was noted at the highest gait velocity (v = 6 km/h) and the lowest step frequency ($f = n - 10\%$). The smallest COM oscillations in vertical direction were twice as low as the highest and their average value was 24 mm; they occurred during locomotion at the lowest velocity (4 km/h) and the highest step frequency ($f = n +$ 10%).

The smallest changes in vertical COM oscillations in men, as a function of step frequency, were recorded at a speed of 5 km/h; in the range of the frequencies applied, this parameter decreased by 9 mm, which in relative terms accounted for around 20%. In both slower gait (4 km/h) and faster gait (6 km/h), the increase of step frequency led to V_{COM} decrease by approximately 30%, while an absolute 16-mm difference was the biggest during the gait at 6 km/h.

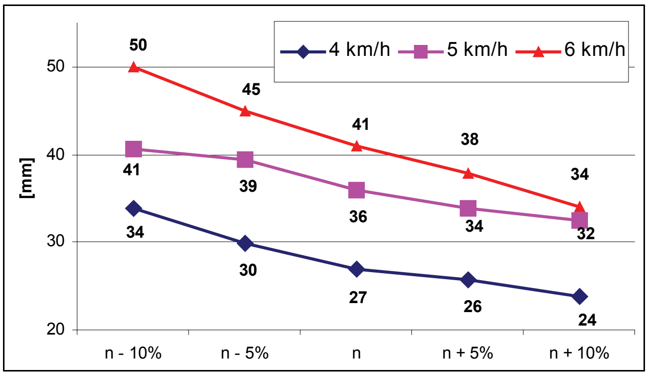

Fig. 6. Absolute values of V_{COM} in men during gait at given velocity and step frequency

The influence of changes in velocity and frequency on the vertical COM oscillations in women is illustrated in figure 7. As we can see, the highest V_{COM} values were recorded during gait at the highest speed (6 km/h). Regardless of the velocity of excursions, step cadency increased as vertical COM oscillations decreased. V_{COM} value during fast walking (v = 6 km/h) was 2 cm smaller, whilst at lower velocities (4 and 5 km/h) those changes were 15 and 10 mm, respectively.

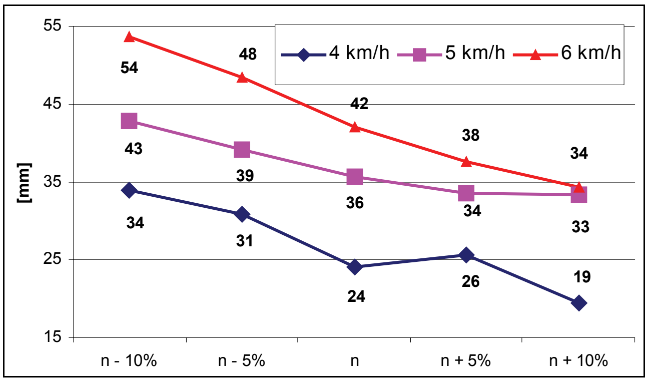

Fig. 7. Changes of V_{COM} in women during gait

The data in figure 8 allow us to determine the effect of kinematical gait parameters (v, f) on lateral COM displacements in men. The highest L_{COM} values (4 cm) were noted at the lowest gait velocity (v = 4 km/h). An increase in speed or frequency resulted in a decrease in lateral COM oscillations. The lowest value of the variable analyzed (L_{COM}), i.e. about 2.5 cm, was found at the highest frequency of steps regardless of the speed of walking.

The changes of lateral COM oscillations during gait in women are presented in figure 9. The increase of step frequency from minimum (n – 10%) to maximum (n + 10%) at all walking speeds in our study resulted in a decrease of lateral oscillations by 11–13 mm.

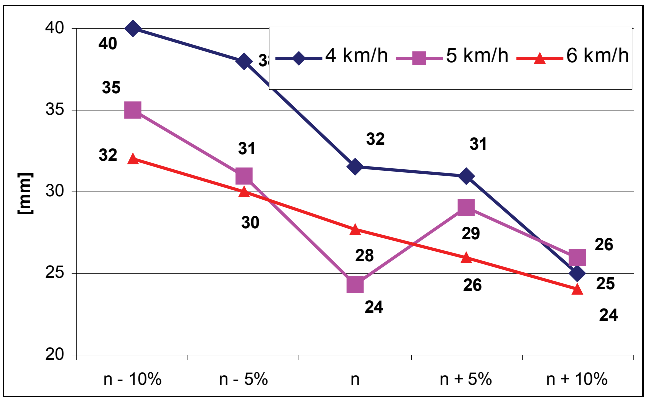

Fig. 8. L_{COM} in men during gait at given velocity and step cadency

The analysis of V_{COM} revealed their similar levels in women and men, and the differences noticed were small (from 1 mm to 5 mm). Referring to L_{COM}, usually higher values were noticeable in men and the discrepancy ranged from 3 to 13 mm; that appeared to be more than 1 cm in 5 of 15 variants of the gait investigated.

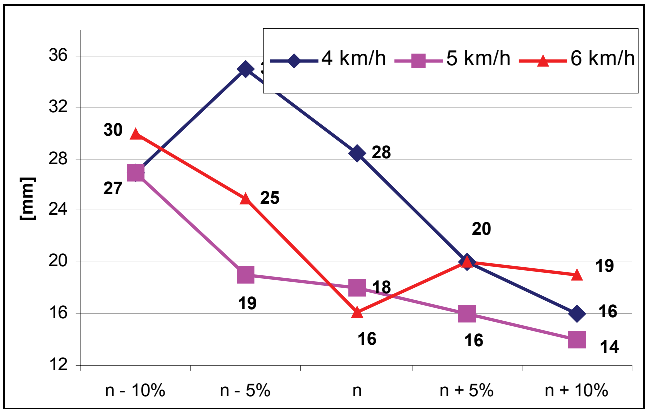

Fig. 9. L_{COM} in women during gait at given velocity and step cadency

4. Discussion

Biomechanical gait analysis can be based on the results of research conducted on various types of the treadmills or on natural ground, usually using the force platforms. The researchers are disputing whether the use of treadmill may have an impact on the results obtained and whether the conclusions from this research can be valid in the description of human gait on the ground. The literature in this field provides the evidence of small differences in the two types of movement [23] and is lacking in such diversity [24]. The purpose of the study was not, however, to settle the dispute about the impact of treadmill on the value of kinematic gait parameters, but this mode of study was chosen as it allows the observation of walking with the same speed in all participants.

The issue of the COM behaviour during gait has been explained in different ways, e.g. by applying force platforms [17], [25], treadmills [26], [27] and video systems [28], [29], [30]. In terms of quality, the shape of the function characterizing COM displacements was similar in every case and the differences were quantified. Functions illustrating vertical and lateral COM transitions (figures 2 and 3) are typical of this type of locomotion. In one gait cycle in women and men, there were noted 4 local extrema referring to vertical oscillations and 2 – to lateral transitions. Identification of these points is a consequence of the presence of two steps during one gait cycle [2]. Vertical oscillations are the effect of two consecutive repeated movements of man where inverted pendulum model was indispensable [31]; however, lateral COM oscillations are accompanied by body weight bearing by feet during successive single support gait phases [32].

The data revealed similarity in vertical COM oscillations in women and men during walking on the treadmill. During natural locomotion there is an increasing trend as walking speed increases from ca. 25 mm (4 km/h) to more than 40 mm (6 km/h). Vertical COM increase during walking at higher velocity has been previously mentioned [21], [25], [27], [30], though the values reported are significantly different, depending on the author. HAHN & CHOU [29] determine this value on the level of 0.04 m, while this is a mean value for young women and men moving at a speed of 4.91 km/h. With Vicon analysis of gait, ORENDURFF et al. [30] noticed vertical COM oscillations reaching 2.74 cm at a velocity of 2.5 km/h.

The results of this research also indicated that while speed was increasing to 5.76 km/h, vertical COM oscillations also increased to 4.83 cm. Unfortunately, the comparison between the results of current research is difficult, considering the fact that most of the data are averaged for small groups; e.g., Orendurff's sample consisted of 10 subjects (7 men and 3 women) [30]. LEE & FARLEY [25] calculated that vertical COM oscillations increased from 0.013 m ($v = 0.5$ m/s) to 0.031 m ($v = 2.5$ m/s) during gait. Also in this case, quantitative comparison with our results is not easy, since COM displacements were evaluated on the basis of ground reaction forces, and – what is more – on a very small group of participants (5). Besides, the results mentioned are the mean values for women and men. To analyze gait on a treadmill using Optotrak system, HOLT et al. [21] established within the values of velocity of 0.6–1.6 m/s (2.16–5.76 km/h) vertical COM oscillations ranging from 20 to more than 40 mm. Unfortunately, these data came from 6 women and 5 men aged 19–41. It seems that comparison of the results of our study with the data of HOLT et al. [21] is accompanied by significant error, especially in view of the investigations of SMITH et al. [28] and HAHN & CHOU [29]. They studied the significance of the age impact on the COM behaviour during gait, which is undoubtedly associated with the changes of body proportion of man in ontogenesis process. As seems, the results achieved by SMITH et al. [28] may provide a valuable basis for comparison with the results of our research. By means of Vicon system, those scientists determined the size of vertical COM oscillations during gait in women and men: 31.1 mm and 38.5 mm, respectively, while men were moving with slightly higher velocity (4.71 km/h) than women (4.57 km/h). As we can see, the results of men are similar to these achieved in our study. As far as women are concerned, the difference of 0.5 cm could arise from two reasons: SMITH et al. [28] have studied considerably older and shorter women (mean age: 30 years old, mean height of the body: 1.60 m).

The differences in the results of the measurement of vertical COM oscillations during gait of women and men were smooth. To prove this fact we can use the data of the study already cited [25], [29], [30], where the results for female and male were averaged. A thorough analysis of these data indicates that the variability of vertical COM displacements was smooth in the group of subjects as it was evidenced by the low value of standard deviation. The conclusion by SMITH et al. [28], to some extent, confirms small differences (only 7 mm) in COM oscillations in women and men. Lots of arguments support the conclusion that this discrepancy would be smaller if Smith and co-workers had studied a little taller women, as the difference in a mean body height of women and men was as large as 20 cm.

An increase in step cadency (figures 6 and 7) is followed by a decrease in vertical COM oscillations. Of course, it is not surprising since a natural consequence of an increase in step frequency at a constant velocity should be a shortened step, which was reported, among others, by ZIJLSTRA & HOF [26] and GORDON et al. [33]. The only astonishing fact is that the largest changes of vertical COM oscillations are noticed at the fastest walking speed (6 km/h).

An increase in step cadency at this relatively high velocity resulted in a decrease of vertical COM excursions in women and men, both by 15–20 mm (at lower gait velocities a high step cadency caused a decrease in oscillations only by 9–15 mm). It seems that so high decrease in vertical COM excursions during walking at high velocity and increased steps cadency is a consequence of a considerable shortening of the movement cycles and the time of one step performing. Walking biomachine is then controlled to minimize lateral and vertical displacements and to maximize the values of parameters responsible for forward body transfer. One can also assume that oscillations of the COM are closely related to the management of energy resources in organism. It is commonly known that together with the increase of velocity and step cadency the cost of energy in walking also increases [10], [33]. One of the possible explanations seems to be the necessity of minimizing vertical COM displacements in order to decrease twice the energy required to COM elevation during one gait cycle. As far as the energy criterion of gait is concerned, this observation can be essential, although it should be stressed that we can find publications raising doubts about such proposals [34]. Lateral COM displacements during gait are more rarely investigated than vertical COM oscillations. This is probably due to the need for more sophisticated measuring apparatus.

The results of this study (figures 8 and 9) indicate that lateral COM displacements reveal a decreasing tendency as gait velocity increases. It is worth emphasizing that at a given velocity of locomotion the lateral COM excursions are decreasing as step frequency increases. These oscillations are slightly higher in men than in women. L_{COM} values in men range from 2.4 to 4 cm, whereas in women from 1.4 to 3.5 cm. At the same time, one should underline that at each value of velocity realized with natural step cadency the lateral COM displacements in men reach 24–32 mm, while in women 16–28 mm.

According to PERRY [2] lateral COM displacement during gait is close to 4 cm. This value is slightly higher than that in natural gait and simultaneously similar to maximal values noted in our research. This author gives no further details on the changes of COM behaviour in gait at unstable velocity and step cadency. Similar values of lateral COM displacements (mentioned by Perry) are reported by CHOU et al. [17] and HAHN & CHOU [29]. The latter paper demonstrates that 4-cm lateral COM displacements are noticed at gait velocity of 4.7–4.9 km/h and that in younger subjects those excursions are slightly higher than in older ones.

The analysis of recent investigations on human gait shows that in terms of an increasing walking speed we observ smaller lateral COM oscillations [27], [30], which is consistent with our results. ORENDURFF et al. [30] established that within the range of 0.7–1.6 m/s, lateral COM displacements are decreasing from 7 cm to 3.85 cm. These values seem to be too high, which could result from the fact mentioned – small study sample (n = 10) and the results averaged for women and men.

A decrease in lateral COM oscillations during gait with large velocities is (like in the case of vertical COM oscillations) a consequence of the control process of this kind of movement. For that purpose use is made of changes of ground reaction forces, appropriate foot position and compensative trunk and upper limbs movements [32]. Taking account of the above, we can state that during fast body weight transition from one leg to another, COM movement in frontal plane is limited due to the duration of gait cycle on the one hand and the size of base of support in coronal plane on the other one.

The most unexpected effect of the research was that the lateral COM displacements during walking are higher in men than in women. This means that such a conclusion is in disagreement with even very apparent gait observation in women. As it turns out, however, identical conclusions we have found in SMITH et al. [28], indicating that lateral COM oscillations in young men are about 10% higher than in women at the same age. Simultaneously, the same research team reveal that the differences in the displacements are disappearing between women and men with age.

In an available literature, there is no information on the relations between step cadency and the values of lateral COM oscillations. However, it is not difficult to assume that such a link exists and its value is negative (compare figures 8 and 9). As was mentioned before, increasing the frequency of steps at stable gait speed results in a shorter length and time.

In the light of up-to-day knowledge and the analysis of our own results, we can conclude that lateral COM oscillations during gait with velocity typical of adults do not exceed 40 mm and are decreasing as the gait velocity and step cadency increase. At the same time the results give rise to the conclusion that the lateral COM excursions in males are larger than in females.

5. Conclusions

The analysis of the results achieved allows the following conclusions:

1. Vertical COM oscillations (V_{COM}) when walking at three different velocities of 4 km/h, 5 km/h and 6 km/h were within 19–54 mm and were similar in men and women.

2. Lateral COM displacements (L_{COM}) in terms of walking velocity from 4 km/h to 6 km/h ranged from 14 mm to 40 mm and were larger in males.

3. During gait with increasing velocity (v) vertical COM displacements increased, while lateral excursions decreased.

4. An increase in step frequency (f) during gait at constant velocity (v) led to reduced vertical and lateral COM oscillations in both women and men.

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