Acta of Bioengineering and Biomechanics
Vol. 14, No. 2, 2012

Original paper
DOI: 10.5277/abb120211

Three-dimensional analysis of the pelvic and hip mobility during gait on a treadmill and on the ground

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Pelvic girdle combines two units: passenger and locomotor. That is why the importance of this part of the body is emphasized by all researchers in terms of gait economy.

The purpose of our research was to determine the changes of pelvic girdle mobility and hip joint in men in three planes of movement (sagittal, frontal and horizontal) during gait at a speed of 5 km/h. The methodology used here aimed at assessing the impact of the surface (ground or treadmill) on the mobility in those planes.

To register overground and treadmill locomotion we applied: Vicon 250, Cardionics Treadmill 3113. The sample of the study was the group of 30 men aged between 21 and 23.

The analysis of the results revealed the biggest impact of the type of surface on both pelvis and hip joint in the transverse plane. When the subjects moved on the natural ground, the pelvic range of motion (ROM) in this plane was more than twice wider than that in treadmill walking. Whereas in the case of hip joint, significantly higher ROM values occurred in the transverse plane during walking on the treadmill.

Key words: *pelvic girdle, range of motion (ROM), Vicon system, walking*

1. Introduction

A considerable body of literature on the biomechanical studies of human locomotion deals with the comparison of overground and treadmill walking. A clear analysis of the conclusions from such investigations is very difficult, if at all possible. The results achieved by different authors are often contradictory and sometimes mutually exclusive. The analysis of our own results and of the work of others seems to indicate that only particular aspects of gait on the ground are similar to treadmill walking. This observation refers to spatio-temporal parameters characterizing both forms of locomotion. Previous studies of STASZKIEWICZ et al. [1] show that temporal parameters of overground and treadmill ambulation differ by less than 5% and are not statistically significant. On the other hand, RILEY et al. [2] describing the values of 22 angular parameters in the joints during locomotion on the treadmill and the natural ground indicate that only 12 parameters differ significantly ($p < 0.05$), but the magnitude of the difference is generally less than 2°. The report of PARVATANENI et al. [3] is found to be in compliance with these investigations. These researchers argue that step, stride and joint angular kinematics are similar for both modes of walking with the exception of the maximum hip flexion and knee extension which are more pronounced with treadmill or overground walking, respectively, but in both instances differ by less than 3°. It should be noted that the vast majority of older studies (e.g., [4], [5]) demonstrates similar findings.

It turns out that the more specific the issue concerning the comparison of gait on the ground and the treadmill, the higher the ambiguity of the conclusions

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Received: August 15th, 2011
Accepted for publication: January 16th, 2012

obtained. Measurements of bioelectrical activity of muscles provide justification for this thesis. RAHIMI et al. [6] notice that the root mean squares of only two rectus femoris and medial hamstring muscles are significantly higher on treadmill than the ground ($p < 0.005$). Only the offset time of the gastrocnemius muscle is significantly earlier on level treadmill than the ground ($p < 0.005$). The results of NYMARK et al. [7] reveal that the overground and treadmill EMG patterns at natural speed are similar with the exception of a slight increase at an initial contact (tibialis anterior), a slight increase in relative peak amplitude (medial gastrocnemius), decreased EMG in early to midstance (rectus femoris and vastus lateralis) and increased peak in late swing (medial hamstrings).

In their study of ground reaction forces in both variants of gait, WARABI et al. [8] state that contact time of the heel on the treadmill is significantly shorter (by 19.8%) than that for floor walking. At the same time PARVATANENI et al. [3] prove that vertical ground reaction force profiles are similar although the peak associated with push-off is 5.5% smaller in treadmill walking.

Considering energy cost in overground and treadmill ambulation, the results achieved in various scientific centres differ significantly [9], [10]. DAL et al. [10] on the basis of preferred walking speed show that the oxygen cost of walking on a treadmill significantly increases compared to walking on the ground. It should be emphasized that in terms of absolute values, the energy cost of both types of gait differs slightly. The last remark becomes more important in view of the results of PARVATANENI et al. [3] who conclude that the metabolic requirements of treadmill walking are about 23% higher than those associated with overground walking.

As a result of the above mentioned results, the researchers involved in locomotion study arrive at one of two general conclusions: first, the lack of relevant qualitative and quantitative differences in the normal gait on the ground and on the treadmill, or the second emphasizing the distinction between these forms of transferring the body. As one can see, the application of the treadmill may be a source of scientific polemics on the impact of this equipment on a manner of human locomotion.

The authors are aware that probably this paper dealing with kinematics in overground and treadmill walking will not solve all these problems ultimately. Nonetheless, the results may become a contribution to the research of this type on a larger scale. What distinguishes this study is the analysis of both types of locomotion changes in pelvic girdle mobility in each of the three major planes of movement. Such an approach takes into account the data of PERRY [11], according to which the issues relating to gait are highlighted by two functional units: passenger unit – head, trunk, upper limbs and locomotor unit – lower limbs. The function of a link between them meets pelvic girdle.

The purpose of this paper was to determine the changes of pelvic girdle mobility and hip joint in men in three planes (sagittal, frontal and horizontal) during gait at a speed of 5 km/h. The methodology used here aimed at assessing the impact of the surface (ground or a treadmill) on the mobility in those planes.

As it seems the experiments carried out can be used not only in biomechanical study of human locomotion, but also in rehabilitation. This topic may also help to assess the treadmill impact on the changes of physiological pattern of gait.

A final note is of particular importance due to the fact that this article represents another, the third part of the description of the matter, published in one the previous issues of "Acta of Bioengineering and Biomechanics" [1, 12].

2. Material and methods

The study of human locomotion was carried out in the Biomechanics Department at the University School of Physical Education in Kraków. The sample of our research was a group of 48 men aged between 21 and 23. The inclusion criteria allowed us to achieve very homogeneous group composed of only healthy subjects without any previous injuries within musculoskeletal system. None of them had practised sport competitively. The participants in our experiment had also to fulfil the criteria of walking speed. Initially, gait on natural surface was carried out by 33 men. The range of walking speed, in this group, was from 3.5 to 6.5 km/h. Along with methodological assumption, we selected only those subjects whose speed was approximately 5 km/h. These requirements met only 15 men. So finally, the measurements were carried out on a sample of 30 men aged between 21 and 23: half of them were walking on the treadmill (T), whereas the rest, on the ground (O). The collection of the data of gait on the treadmill was based on the trials when the belt was moving at a speed of 5 km/h. This approach makes our assessment of differences in the locomotion independent of the speed which, as is well known, affects gait pattern.

The choice of such a velocity was made based on the previous observations showing that lower velocities were not comfortable for the subjects. Simultaneously, in the case of higher speeds, there was a risk of uncontrollable change of the way of locomotion from walking to running.

Morphological parameters of the research participants were as follows ($\overline{X} \pm SD$): body height 1.81 ± 0.04 m and body mass 78.7 ± 8.42 kg. In the group of the subjects performing overground ambulation, the average height and weight were, respectively, 1.82 ± 0.09 m and 77.8 ± 11.2 kg.

The most important element of measuring set was a system of three-dimensional analysis of the movement (Vicon 250). In both variants of walking, the subjects were moving within the space of Vicon system, either on a treadmill (Treadmill Cardionics type 3113), or on the ground. The locomotion was registered by five video cameras emitting infrared light, reflected by the markers placed on the subject's skin according to the Golem model (39 markers). 4 markers were placed on the head, 4 on the trunk, 3 on the pelvis and 7 on each of the upper and lower limbs. 15 complete gait cycles for each leg were recorded for all patients. Angular changes were averaged over trials of all the subjects walking on the ground and the treadmill. Each person during measurements worn only a comfortable, sporty footwear and sports clothing.

External conditions in the room (humidity and temperature) were similar for each subject. After the calibration of the measuring system the subjects realized gait in accordance with the planned methodology. The results enabled the comparison of the selected parameters of natural gait at 5 km/h on the ground and on the treadmill.

To investigate the normal distribution of the results in the groups we used the Shapiro–Wilk test. Analogous pairs of variables in both groups were tested by Student's *t*-test for independent groups considering significant statistical differences at $p < 0.001$.

In the present study, we used the terminology of PERRY [11], and while plotting graphs we used the so-called normalized gait cycle (GC), in which the duration of one cycle was defined as 100% GC.

3. Results

Figures 1–3 illustrate angular changes of the pelvis in all three planes during gait at the speed of 5 km/h realized by men on different types of the surface.

Figure 1 shows a significant impact of the surface on a pelvic girdle mobility in the sagittal plane during walking. As can be seen, pelvis is at anterior tilt in overground and treadmill walking, but the values in both types of locomotion are different.

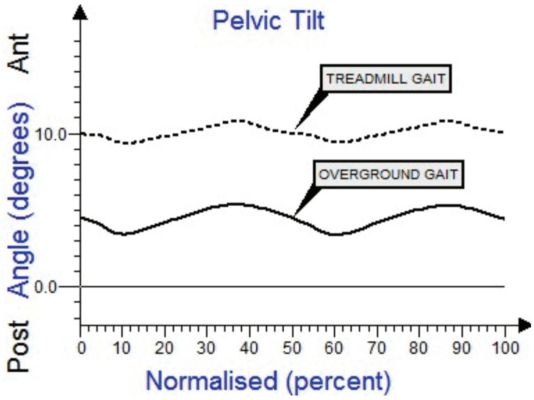

Fig. 1. Pelvic angle in the sagittal plane in men during overground and treadmill walking

Comparison of changes in pelvic mobility in the frontal plane during gait (figure 2) reveals that the type of surface in no way differentiates this variable. In the whole cycle (0–100% GC), the angle was almost identical.

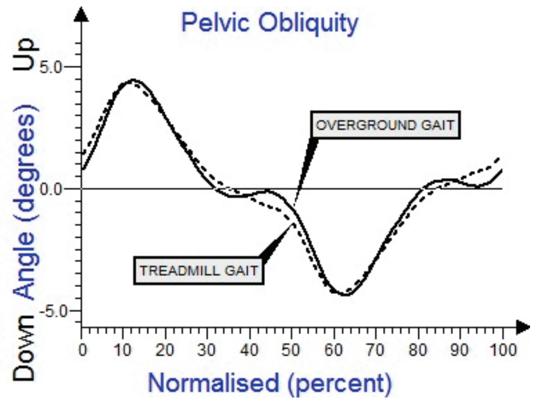

Fig. 2. Pelvic angle in the frontal plane in men during overground and treadmill walking

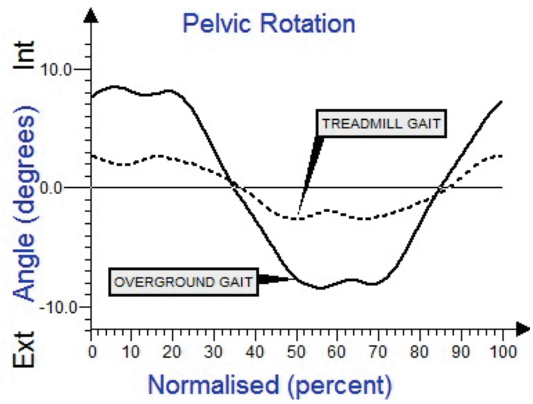

Fig. 3. Pelvic angle in the transverse plane in men during overground and treadmill walking

The biggest impact of the surface used in gait analysis was observed for pelvic movements in the transverse plane. Figure 3 shows that the functions for overground and treadmill gait differed in qualitative and quantitative terms. When our subjects moved on the natural ground, pelvic range of motion in the transverse plane was more than twice wider than that in treadmill walking (16° and 6°).

The analysis of the surface impact on the pelvic girdle mobility in the sagittal and transverse planes paved the way for determining the motion of the hip angular changes in those planes of movement. Figures 4–6 are the basis of that evaluation.

Angular changes in the hip joint (figure 4) in men during walking on a natural ground and on the treadmill showed that the type of surface differentiated these values, but only during the contact phase (0% to about 60% GC). The values recorded during treadmill walking within this range were about 2–3° higher than those in overground gait. Despite the slight difference at the beginning and at the end of the cycle in the angular values in both variants of gait, the hip angles were similar and ranged from 43 to 45°.

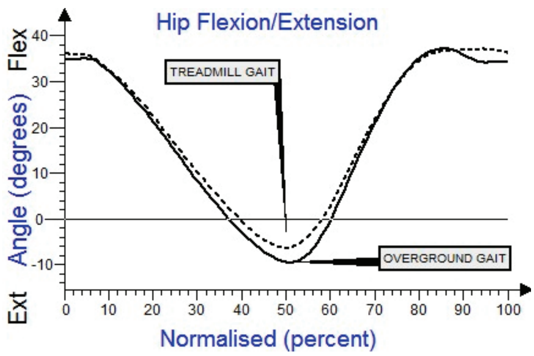

Fig. 4. Hip angle in the sagittal plane in men during overground and treadmill walking

The type of the ground on which the subjects were walking did not affect the hip range of motion in the frontal plane (figure 5). The values of this parameter in men ranged from 12° to 13°. In both types of locomotion, the greatest diversity of the instantaneous value of the hip angle occurred in the extremes of the cycle (0% and 100% GC). The instantaneous values of the angle analyzed varied from 1° to 4°, except for the range from 40% to 60% GC. It turned out that in this part of the cycle the type of surface had no effect on the hip abduction/adduction.

Even a brief analysis of figure 6 shows a significant effect of the type of walking on basic values registered in the hip angle in the transverse plane. The greatest differences were found in the second half of the gait cycle (50–100% GC), and especially during the transfer of the limb. In this part of the cycle, there was a total change in the nature of movement: in the treadmill walking we could observe internal rotation of the hip joint, whereas in overground walking this joint movement appeared to be in the opposite direction, and vice versa. Consequently, during walking on the ground the hip joint is positioned in a small internal rotation in initial contact phase, and in treadmill walking in external rotation.

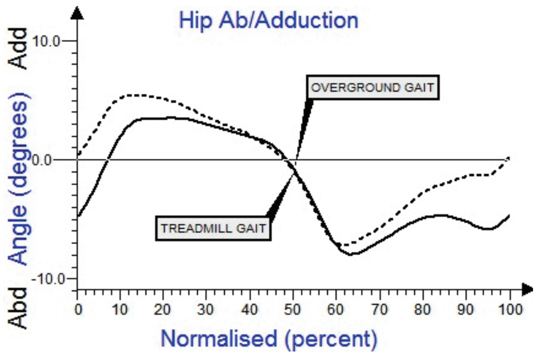

Fig. 5. Hip angle in the frontal plane in men during overground and treadmill walking

Differentiation of hip angle in the transverse plane, depending on the type of movement, resulted in changes in the range of motion. ROM value in walking on the treadmill was over 30° and was more than three times higher than that in overground gait (10°).

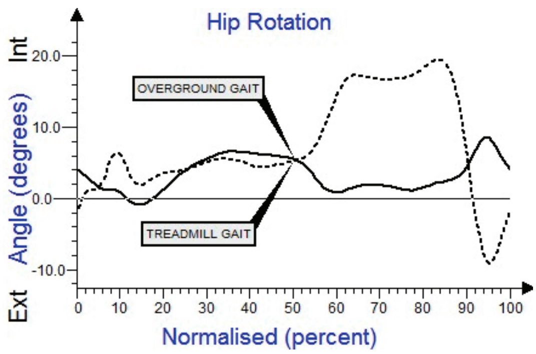

Fig. 6. Hip angle in the transverse plane in men during overground and treadmill walking

In the next stage of analysis, we assessed the significance of differences between mean values of analogue variables in both variants of gait. We also evaluated the ranges of motion of the pelvis and hip joint in each of the three major planes of movement. The table shows the statistical characteristics of these parameters and the results that verify the hypothesis about the significance of differences (Student's *t*-test for independent groups).

Table. Descriptive statistics of hip and pelvis ranges of motion (deg) during gait on the ground (O) and on the treadmill (T). *** – statistically significant differences

		$x \pm SD$	max	min
Pelvic tilt	O	2.2 ± 0.51	3.2	2.1
	T	2.3 ± 0.61	3.4	1.0
Pelvic obliquity	O	8.8 ± 2.18	12.9	4.9
	T	8.6 ± 2.10	12.0	5.6
Pelvic rotation***	O	16.8 ± 4.43	23.1	13.6
	T	6.3 ± 2.45	9.5	3.1
Hip flex/ext	O	43.9 ± 3.51	51.8	33.7
	T	44.4 ± 3.73	55.7	39.0
Hip abd/add	O	12.4 ± 2.26	17.1	8.8
	T	13.1 ± 3.28	20.9	8.0
Hip rotation***	O	10.5 ± 2.63	16.3	6.8
	T	30.2 ± 5.39	39.3	22.4

*** $p < 0.001$.

The analysis of the table reveals statistically significant differences only in the case of the range of motion in the transverse plane (rotational movements). This observation applies to both pelvis and hip joint.

4. Discussion

From the standpoint of determining the impact of the surface on the changes of pelvic mobility in each of the three major planes of movement, these studies appear to be unique, because there has been no solid research in this field. In literature of the subject, there is little description of 3D analysis of pelvic girdle mobility during walking on a treadmill and on the natural surface. This observation is surprising since the importance of this part of the body for economy of the movement is emphasized by all researchers defining the so-called gait determinants [13]. Additionally, pelvic girdle combines two units: passenger and locomotor [11].

The present results show that the walking on the treadmill significantly decreases pelvic girdle range of motion in the transverse plane. The type of surface, to a lesser extent, affects the instantaneous values of anterior tilt of the pelvis, whereas in the frontal plane there are no differences in the pelvic motion between gait realized in traditional conditions and on the treadmill. As it seems, these observations are a consequence of the movement of a treadmill belt, where gait is performed. On the one hand, the subjects seek to ensure their safety which is reflected in an increasing area of support. On the other hand, the body posture of a man moving on a treadmill is characterized by the tendency to lower the center of gravity with respect to the ground, as reported, e.g., [6]. It seems that one of the ways to achieve this goal may be an increase of pelvic anterior tilt just described.

The increase in the pelvis ROM in the sagittal plane reported in this paper is, of course, active and required by the appropriate muscle work. To verify the latter statement it would be necessary to conduct an adequate study of EMG. An available literature on the studies of electrical signal in the muscle is not involved in this kind of phenomena. In contrast to active changes of gait pattern occurring in pelvis in the sagittal plane, changes in the transverse plane were passive. The movement of this part of the body was performed using a treadmill belt movement and its speed. This was possible because the directions of the pelvis motion during lower limb contact with the ground and the treadmill belt were similar. The results obtained and their analysis are confirmed in the study conducted by RILEY et al. [2]. These researchers, using the Vicon system, show significant differences in the pelvic mobility between overground and treadmill walking. It is interesting that they demonstrate that differences exist in each plane of movement. It seems that the interpretation explaining the relationship between the position of the pelvic girdle and the type of ground on which you are walking is correct. However, this issue may be a contribution to further, detailed studies carried out on a larger scale.

Our study shows that the hip range of motion in the transverse plane is significantly wider in the treadmill than in overground walking. Additionally, in this plane of motion, angular changes in the phase of limb advancement are for the two variants of gait qualitatively different. Consequently, a graphical record of these changes in this part of the cycle in normal gait is a mirror image of the recording obtained for the movement on the treadmill. If the width of the steps while walking on the treadmill sometimes is higher than that under normal conditions [14], it should be the result of the increased external rotation of the hip. Thus, a wider range of motion and instantaneous angle in the transverse plane. This kind of observation will be more clear, if the movement of the pelvic girdle in the transverse plane will be more reduced. As is known, such an observation is made in this study. The above-mentioned reasoning is supported by the data of RILEY et al. [2]. They found significant differences in the mobility of the hip in the transverse plane. Probably, EMG studies of the hamstrings, especially biceps femoris, could justify these differences. As we know, biceps femoris, although it belongs to the group of knee flexors, really cooperates in external rotation of the thigh. First such research has been already performed, but the following results are not conclusive [4], [15], [16].

Comparison of walking on the ground and on the treadmill, in the case of hip joint angular changes in the sagittal and frontal planes, shows no differences in respect of these forms of locomotion. Our earlier studies have shown that in flexion/extension movement, the most distinctive changes during gait on the ground and treadmill appeared in the ankle joint. This seems obvious, since on this lowest level of the closed kinematic chain created by a lower limb, a safe loading phase of the foot takes place. In terms of locomotion safety, on higher levels of this mechanism other tasks are solved. Flexion of the hip and knee joints provides functional shortening of limb in order to avoid hooking it to a moving treadmill belt. Our own results show that the average range of motion of the hip in the sagittal plane is close to 44°. These values correspond well to the data by WATELAIN et al. [17], although it should be noted that in the study conducted by DUJARDIN et al. [18] the average amplitude of this movement was 31°. In addition, the ambiguity of the results is reinforced by some older studies. For example, JOHNSTON and SMIDT [19] show slightly wider ranges of flexion/extension of the hip joint during gait. Manifestation of changes in the control of the lower limb is also a fact of slightly different location of the hip in the frontal plane. We observe that during treadmill gait, at the beginning and end of the cycle (0% and 100% GC), the joint is set in the neutral position, while walking on the floor it stays in a few-degree abduction. It is possible that reported previously functional shortening of the lower limb in swing phase is a necessary and sufficient condition for ensuring that walking on the treadmill is made safely, without increasing the angle of hip abduction. Interestingly, in contrast to the values describing angular parameters in the sagittal plane, both our own research and all those above mentioned, so new and old [17], [18], [19], assessed similarly the range of abduction/adduction during gait.

The results should be considered as preliminary. Since the way of walking requires some changes in mobility of pelvic girdle in men, it should be absolutely verified in women. This observation seems to be the basis for qualitative assessment of the impact of physiological state on the pattern of locomotion in, e.g., pregnant women.

5. Conclusions

The analysis of the results of the natural walking at a speed of 5 km/h, realized by men on the ground and on the treadmill, has allowed the following conclusions:

1. The differences in the way of movement on the treadmill and on the ground are revealed by the analysis of angular changes of the hip and pelvis. The type of the surface used in gait affects the range of motion, the instantaneous values of angles and the dynamic changes in these values.

2. Treadmill walking is characterized by a much greater range of movement of the pelvis in the transverse plane compared to sagittal one. The type of surface, to a lesser extent, affects the instantaneous values of anterior tilt of the pelvis, without affecting in any way the change of its motion in the frontal plane.

3. Comparison of the hip angular values in both variants of gait testifies to significant differences in the transverse plane, while in other planes of motion (sagittal and frontal) differences were not significant.

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