Acta of Bioengineering and Biomechanics
Vol. 14, No. 1, 2012

Original paper

Influence of surface on kinematic gait parameters and lower extremity joints mobility

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In biomechanical studies of human locomotion, treadmill is a widely used measuring device. The purpose of this paper was to determine the values of kinematic parameters describing gait with the velocity of 5 km/h, both on the ground and on a treadmill. Besides, the authors assessed the impact of the surface on the mobility of three main joints of lower extremities in the sagittal plane. The measurements were done on a sample of 48 men aged between 21 and 23. The most important element of a measuring set was the Vicon system. Based on kinematic parameters our data indicated that during walking on a treadmill step frequency was slightly higher than that on the ground. Probably, due to that fact there were found some differences in other variables (e.g., single support as well as step and stride time). Besides, the results revealed that the type of surface affects joint range of motion, in particular ankle plantar flexion, the instantaneous values of joint angles and change in dynamics of these values.

Key words: *overground vs. treadmill walking, spatio-temporal parameters, joint angular changes*

1. Introduction

Gait is a fundamental form of human locomotion [1], [2]. The length of ontogenetic period and noticeable individual variability are the reasons for the work of many researchers in this field. Someone's inability to walk as a result of injury or illness becomes the source of a series of existential complications more serious than only physical lack of ability to transfer.

That impairment of vital functions raises serious psychological consequences. These, e.g., the specific mapping of the psychophysical state in the way of locomotion, have been the subject of many works [3]–[5] giving the evidence of such relationships.

Reducing the negative consequences of patient's immobilization, or withdrawing from the results of diseases, as well as replacing the deficiencies in passive and active movement apparatus with technical equipment – these are in the field of engineers' interest. The result of this kind of activity seems to be incredibly essential in terms of locomotion referring to a man with some limited movement capacity.

In biomechanical studies of human locomotion, treadmill is a widely used measuring device [6]–[11]. Beside some obvious advantages of its use, it constitutes a source of several controversies. Objections allow us to get answers to some basic questions. Does the movement on the treadmill reflect natural locomotion on the ground? Does the pattern of locomotion change as a result of a treadmill use? And finally, whether the results of the research conducted using the treadmill can be transferred without any objections to each manner of walking?

Researchers have been looking for the answers to such questions for a long time [2], [12]–[15]. The improvement in research methods, in particular the ways of precise movement registration, proved to be very helpful. An available literature provides some investigations which reveal the differences in the way

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Received: April 5th, 2011
Accepted for publication: December 28th, 2011

of walking on the ground and on a treadmill [11], [13], [16]. But there are also some researchers who do not find any differences [2], [14]. Of course, the results of such research are, to some extent, erroneous. As is widely known, the way of locomotion depends on gender, age, health and the speed of movement [17]–[20]. Besides, when using a treadmill in the research, time seems to play an important role in adaptation to the new conditions of the movement, which has real meaning in the studies of older people, because this kind of measurement can cause many problems.

The purpose of this paper was to determine the values of basic kinematic parameters describing the gait with a velocity of 5 km/h on the ground and on a treadmill. The methodology used allowed us to assess the impact of the surface on the mobility of three main joints of lower extremities (ankle, knee and hip) in sagittal plane.

As it seems, the experiments carried out can be used not only in biomechanical study of human locomotion, but also in a movement rehabilitation in the process of improving the subjects with the history of injuries and trauma. The issue settled helps also to determine the importance of a treadmill impact on the physiological gait pattern.

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 measurements were done on a sample of 48 men aged between 21 and 23. All persons described their health as good and declared that in the past they did not suffer from any significant injuries to passive or active system of the movement that could affect the registered activity. None of these people had practised sport competitively. The authors felt entitled to compare both groups of subjects because they did their best to guarantee the comparable conditions.

Half of the men examined were walking on the treadmill (T), whereas the others on the ground (O). Initially, a gait on natural surface was realized by 33 men. In this group, a gait speed ranged from 3.5 to 6.5 km/h. According to methodological assumption of our research, we selected only those men whose speed of locomotion was approximately 5 km/h. These conditions were fulfilled by 15 men whose morphological data are presented below. The next stage of the study was to collect data of men's gait on the treadmill, where 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 criterion of velocity was based on the previous studies indicating clearly that lower velocities were not comfortable for the subjects. At the same time it was noticed that 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 subjects were as follows ($\bar{x} \pm SD$): 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 mass were 1.82 ± 0.09 m and 77.8 ± 11.2 kg, respectively.

The most important element of measuring set was the system of a three-dimensional analysis of the movement (Vicon 250). The subjects, depending on the option of walking, were moving in the space of Vicon system, either on a treadmill (Treadmill Cardionics type 3113), or on the ground. Five video cameras that emit infrared light reflected by the markers placed on the subject's skin registered their results. In the present study, to map the body we used the so-called Golem model (developed by the creators of the system), which required placing 39 markers on the body. 4 of them were placed on the head, 4 on the trunk, 3 on the pelvis and 7 on each of the upper and lower limbs. In all patients, about 15 complete gait cycles were recorded for each leg, and mean values of all variables of the recorded cycles were analyzed. Each person during the 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 a gait according to the methodology adopted. The resulting record of research referred to the gait technique and modelling, which enabled us to obtain the values of kinematic parameters of movement (in the form of numbers, graphs, tables) and its spatial picture (animation). The results made it possible to compare the selected parameters of natural gait at 5 km/h on the ground and on the treadmill.

Our article uses the terminology proposed by PERRY [21]. According to her definitions, in both variants of gait we apply statistical characteristics of the following variables: step cadency (CAD), single support time (SST), double support time (DST), foot off (FO), opposite foot contact (OFC), and opposite foot off (OFO). Additionally, we present, in the form of graphs, angular changes in three major joints of lower limbs (hip, knee, ankle) in the sagittal plane. While preparing the graphs we adopted the principle illustrating joint flexion with positive values, whereas extension movement was presented with negative values. For each of the subjects there were noted extreme angular values in particular gait phases. The analysis considered the following angles:

AF_{TST} – maximal ankle dorsi flexion in TST (late single limb support),

AF_{PSW} – maximal ankle plantar flexion in PSW (terminal double stance),

KF_{LR} – maximal knee flexion in LR (shock absorption phase),

KF_{MST} – minimal knee flexion in MST (midstance phase),

KF_{ISW} – maximal knee flexion in ISW (initial swing phase),

HF_{LR} – maximal hip flexion in LR (shock absorption phase),

HE_{TST} – maximal hip extension in TST (late single limb support).

In order 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 at a significant statistical difference $p < 0.05$.

In verbal description of the landmarks applied in the graphs, we used the so-called normalized gait cycle, in which the duration of one cycle was 100% of gait cycle (GC).

3. Results

Table 1 contains the mean values of the kinematic parameters describing the gait of men at a speed of 5 km/h. Data indicate that during walking on a treadmill the step frequency was slightly higher, but regardless of the surface, the value of this variable was less than 2 Hz (about 120 steps/min).

Probably, due to a step cadency in both variants of gait, some differences in other variables arose. An absolute value of single support and step and stride time varied from 0.02 to 0.05 s. The length of foot off phase during treadmill walking was about 1% longer than that during walking on the ground. On the other hand, the relative ratios: opposite foot contact and opposite foot off were almost stable in both types of gait.

As a result of Student's *t* test carried out for analogous variables in the groups of men, statistically significant differences were observed in step cadency, the time of support phase, step time, stride time ($p < 0.05$) and single support time ($p < 0.01$) (table 2).

Table 2. Student's *t* test results for spatio-temporal parameters in independent groups during treadmill and overground walking

Variables	*t*	*p*
T CAD vs. O CAD	2.516635	0.018*
T SST vs. O SST	–2.84705	0.009**
T DST vs. O DST	0.589275	0.561
T FO vs. O FO	2.526651	0.018*
T OFC vs. O OFC	1.321441	0.198
T OFO vs. O OFO	1.479149	0.151
T ST vs. O ST	–2.75719	0.010*
T STT vs. O STT	–2.39117	0.024*

* $p < 0.05$. ** $p < 0.01$.

T – treadmill walking, O – overground walking, CAD – step cadency, SST– single support time, DST – double support time, FO – foot off, OFO – opposite foot off, OFC – opposite foot contact, ST – step time, STT – stride time.

Figures 1–3 present angular changes of the main lower extremity joints (hip, knee and ankle) in the sagittal plane in men realizing gait in two variants. As can be seen, in terms of quality, the curves for each joint and for each type of the surface were similar to each other. Quantitative analysis confirmed that the largest differences in angular values were observed in both forms of locomotion (overground and treadmill) in relation to the ankle, while the smallest appeared in the hip joint. The effect of surface type on angular changes in knee joint can be considered to be an intermediate between the mentioned changes in the hip and ankle.

The analysis of angular changes in the hip joint (figure 1) in men allows us to state that the type of surface affects those values only at the beginning (0–10% GC), just before the end of the cycle (90–

Table 1. Basic kinematic parameters of gait at the speed of 5 km/h in men (mean±*SD*)

	CAD* (steps/min)	DST (s)	SST** (s)	ST* (s)	STT* (s)	FO* (%GC)	OFC (%GC)	OFO (%GC)
O	113 ± 5.2	0.25 ± 0.03	0.41 ± 0.02	0.54 ± 0.03	1.07 ± 0.05	61.5 ± 1.3	49.8 ± 0.4	11.7 ± 1.3
T	118 ± 5.9	0.25 ± 0.03	0.39 ± 0.02	0.51 ± 0.03	1.02 ± 0.05	62.6 ± 1.1	50.0 ± 0.4	12.4 ± 1.0

* $p < 0.05$, ** $p < 0.01$.

100% GC) as well as and in the middle of gait cycle (from about 35% GC to about 65% GC). Within these ranges the values recorded approached 2–4°. Despite the slight differences, the range of motion in the hip joint in a sagittal plane in both types of gait was similar and ranged from 43 to 45°.

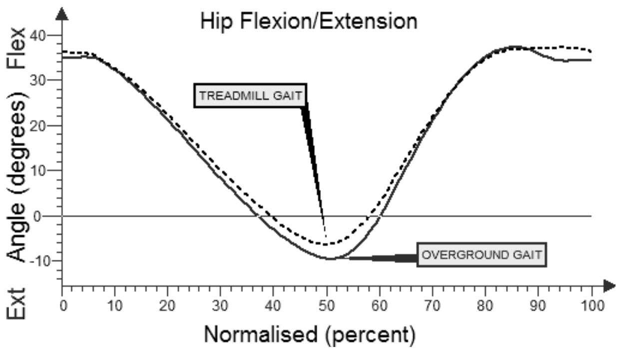

Fig. 1. Hip angle in the sagittal plane in men during overground and treadmill walking

Figure 2 demonstrates angular changes of the knee joint in the sagittal plane during gait at a speed of 5 km/h. This joint range of motion was approximately 55° during treadmill walking, and about 60° in its overground version. At the same time, instantaneous angular values in both variants of locomotion become different. The analysis of the knee movements suggests that in men the type of surface changes the process of contact phase (from 0% GC to about 60% GC) stronger than limb advancement, but the largest differences do not exceed 5–6°.

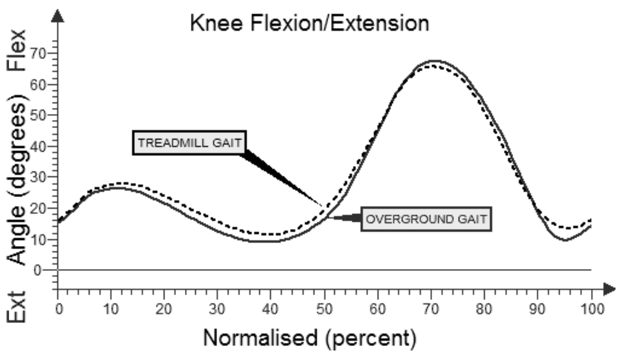

Fig. 2. Knee angle in the sagittal plane in men during overground and treadmill walking

The curves in figure 3 allow us to assess the impact of surface on ankle angular changes. The analysis shows that the amplitude of changes in treadmill gait is about 50% larger. The ranges of motion in the sagittal plane amount to 37° and 26°. The functions representing overground vs. treadmill walking at a speed of 5 km/h differ in men not only in their shapes, but also in their instantaneous values. The greatest variation occurrs in the second half of the gait cycle (from about 50% GC). Although the maximum values of dorsiflexion before the end of support are similar in both types of movement (13°–15°), the plantar flexion at the beginning of the swing phase (about 60% GC) is twice as high as that in treadmill walking (24° and 12°, respectively). In the last part of the gait cycle (80–100% GC), a considerable variation in the ankle joint motion is observed. The differences are related to the angular values, as well as to the dynamics of their changes and, finally, to the type of the movement registered in this joint.

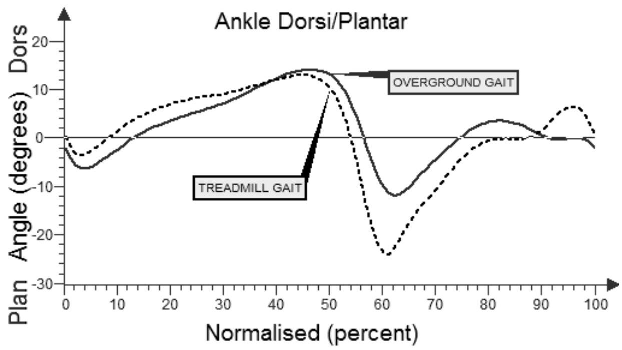

Fig. 3. Ankle angle in the sagittal plane in men during overground and treadmill walking

Table 3. Student's *t* test results for angular changes in independent groups during treadmill and overground walking

Variables	*t*	*p*
T AF_{TST} vs. O AF_{TST}	1.009649	0.320
T AF_{PSW} vs. O AF_{PSW}	4.396457	0.000^{**}
T KF_{LR} vs. O KF_{LR}	–0.39059	0.699
T KF_{MST} vs. O KF_{MST}	–0.55251	0.584
T KF_{ISW} vs. O KF_{ISW}	–2.90697	0.006^{**}
T HF_{LR} vs. O HF_{LR}	2.017119	0.052
T HE_{TST} vs. O HE_{TST}	–2.13512	0.040^{*}

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.
T – treadmill walking, O – overground walking,
AF_{TST} – maximum ankle dorsiflexion in TST,
AF_{PSW} – maximum ankle plantar flexion in PSW,
KF_{LR} – maximum knee flexion in LR, KF_{MST} – minimum knee flexion in MST, KF_{ISW} – maximum knee flexion in ISW, HF_{LR} – maximum hip flexion in LR,
HE_{TST} – maximum hip extension in TST

On the basis of the tests carried out for analogous variables characterizing extreme values of angles we identified significant differences in the maximum hip extension during TST ($p < 0.05$), the maximum knee flexion during ISW ($p < 0.01$) and the maximum dorsiflexion of ankle joint in PSW ($p < 0.001$). Other angles showed no statistically significant differences.

4. Discussion

A considerable body of literature on the biomechanics of human locomotion deals with the comparison of overground and treadmill walking. A clear analysis of the results of such investigations is very difficult, if at all possible. The results obtained by different authors are often contradictory and sometimes mutually exclusive. It turns out that the more specific the purpose of research, the higher the ambiguity of the conclusions obtained.

The results of measurements referring to bioelectrical activity of the muscles [2], [12], [15], [22], [24], ground reaction forces [16], [25], [26] or, finally, energy cost [2], [6], [27] of these forms of locomotion provide justification for this thesis. As a result, the researchers arrive at one of two general conclusions: according to the first one there is a distinct lack of relevant qualitative and quantitative differences in the normal gait on the ground and on the treadmill [8] and according to the second one there is a distinction between these forms of movement [13], [16]. In practice, e.g., in physiotherapy, such a discrepancy of the results cannot be ignored. In this case, except the obvious advantages resulting from the treadmill use in the process of improving the patient's gait, there are natural questions about the effects of such proceedings, or the effect of the surface type on the pattern of gait.

The analysis of our own results and those of other authors seems to indicate that only in certain aspects the gait on natural ground is similar to walking on a treadmill. Indeed, the comparison of the spatio-temporal gait parameters shows a discrepancy of the results. Let us compare the results obtained in this area by, e.g., STOLTZE et al. [13] and GREIG et al. [14]. The first team proves that the kinematic parameters of overground and treadmill walking have different values, while the second team shows a mechanical similarity between two variants of locomotion.

As is widely known, one of the fundamental kinematic gait parameters is step frequency. The accuracy of measuring this variable is essential for the determination of the so-called natural frequency of gait. The analysis of the literature on temporal gait parameters does not provide unequivocal conclusion, although it seems that the studies indicating higher frequency of walking on a treadmill prevail [11], [13], [16], which is confirmed also by our study (table 1). This is especially true when the differences in the frequency between both gait variants are statistically significant. It is worth mentioning that, for example, MURRAY et al. [2], GRIEG et al. [14] and RILEY et al. [8] found no such differences. Our research confirms the results of the first group of the quoted authors (table 1).

OWINGS and GRABINER [28] emphasize that while walking on a treadmill, the variability on the step width is significantly greater than that of the step length. This may suggest the impact of a belt movement of the treadmill on the size of the lateral displacements of the center of gravity of a moving man. BELLI et al. [26] reveal that such an eventuality is a real demand. These authors suggest that in the studies of locomotion such kinds of treadmill should be applied that are characterized by a minimum belt speed oscillations, both under a load and without it. This purely technical note was forced by the necessity of removing interference of the signal during gathering the data. However, this corresponds to the previously announced postulate of SCHENAU's [29] that if the speed of a treadmill belt is biomechanically constant, there should be no differences between the two walking modalities. Thus, an effort to increase the base of support in the lateral direction is a consequence of deficiency in the treadmill and a part of the adaptative controls that the body uses to maintain posture during a walk [28].

Hence, not only PARVATANENI et al. [6] emphasize the necessity of longer periods of familiarizing with to treadmill walking before testing it. Otherwise, researchers are inclined to consider motor adaptation processes of walking on a treadmill and individual differences in motor strategies in this movement. And as we all know, this strategy is directly associated with the processes of coordination, which are much more variable and complex in terms of walking on a treadmill as evidenced by STOLZE et al. [13].

The variation of step frequency in our study may additionally be explained by LEE and HIDLER's work [7]. They reveal that it is extremely difficult to obtain identical measuring conditions in overground and treadmill gait. Of course, all investigators have to face these problems. So, it must be assumed that the differences found by us in step frequency can stem from each of the factors described in the literature quoted above.

Our own results (table 1) show that the values of the temporal parameters of treadmill gait and walking on the ground are similar. The differences observed do not exceed 5%, but in the majority of cases they are statistically significant. This observation is in opposition to the results of LEE and HIDLER [7] and PARVATANENI et al. [6]. They did not confirm statistical significance, although they noted its occurrence. At the same time, it should be stressed that older papers, e.g., [11], prove such differences. It seems that the ambiguity of the results arises when methods of studies are different (the kind of a treadmill and the technique used to record the movements, the total number of subjects in the group and the description of the results for both sexes). Of course, a qualitative comparison of the temporal gait parameters observed by different authors is much more difficult. As we know, the duration of the gait cycle varies with the speed and frequency [30].

As a consequence of changes in cycle time, there is a change in the duration of the remaining gait variables (double and single support, step and stride time). Thus, individual researchers achieve differing values of these parameters. The diversity of results does not change even if the studies use the so-called natural walking speed or free step frequency [10], [17]. This is because human gait is individually variable [1], [21], which obviously affects the number of biomechanical parameters measured during this type of locomotion. These results suggest that the external images of walking on the treadmill and on the natural surface reflected in the temporal parameters are very similar.

The results of this study show that the differences in the way of movement on a treadmill and on the normal surface become apparent during the analysis of angular changes in the lower extremity joints. In the biomechanical literature, the data on angular changes of the main joints of the limb during gait are available [6], [21], [24]. It is worth mentioning that the vast majority of work is concerned only with angular parameters in the sagittal plane. Our own results revealed that the type of the surface used in the gait analysis affects the range of motion, the instantaneous values of angles and the dynamic changes of these values. This observation corresponds to the results of the above authors. Only NYMARK et al. [12] show no difference in the case of angular joints parameters while walking on the traditional ground and on the treadmill.

It should be noted, however, that Nymark et al. who carried out their research at the speed of movement as low as possible, both in the hip (figure 1) and knee joint (figure 2), showed a significant qualitative and quantitative similarity of angular parameters listed in both variants of gait. Absolute differences in the instantaneous values recorded for both types of surface were small and approached 3° for the hip and about 6° for the knee. Although these differences were not large, they were statistically significant in TST phase (hip joint) and in ISW (knee joint). In turn, in the ankle joint (figure 3), very significant differences were observed in the angular value, depending on the surface on which the walk took place. These differences were revealed both in the range of motion in one gait cycle and in the amount of plantar flexion at the ankle joint in foot off phase. For both parameters, the values quoted for walking on a treadmill were, on average, two times higher and additionally statistically significant.

Comparison of joint angles during overground and treadmill walking resulted in unclear conclusions. On the one hand, LEE and HIDLER [7], PARVATANENI et al. [6] and TULCHIN et al. [32] noticed some differences (between 2° and 3°) for hip, knee and ankle, but rated them as slight and insignificant. On the other one, ALTON et al. [11] found significantly greater hip range of motion and its flexion angle during gait on a treadmill.

RAHIMI et al. [22] gave information about the specific impact of the treadmill on angular changes in the knee joint. According to these researchers, in people performing this form of locomotion there is observed a significant increase in the flexion of this joint. The analysis of the results and their comparison with an available literature allows a conclusion that treadmill walking does not significantly affect the value of angular variation in the hip and knee compared to normal gait. At the same time, literature does not reveal such great differences in ankle joint angle as in the present study. It looks as if there were certain conditions to apply in both types of gait differences in this aspect. The movement of a treadmill belt seems to be pushing for more plantar flexion of the foot in the final phase of preswing.

One of the reasons of a wider range of foot plantar flexion during treadmill walking in comparison with normal gait may be the backward movement of the center of foot pressure in the rolling phase, associated with the treadmill movement.

As everyone knows [21], the maximum involvement of plantar flexor muscles of the foot occurs during TST (eccentric work), which means, prior to maximum plantar flexion (PSW). Thus, the movement of the foot in the direction of plantar flexion is the result of the heel off and creates favourable mechanical conditions for the displacement of the plane of support in the direction of the forefoot (the so-called "the forefoot lever").

Extended gastrocnemius muscle works then (in PSW) in favour of the foot as a spring causing it to quickly move down. Co-operation of two elements: the treadmill belt moving backwards and the specific work of the gastrocnemius muscle causes the effect of larger foot plantar flexion as compared to normal gait.

It cannot be excluded that the movement in this joint is affected by the tendency to increase both the base of support in the lateral direction and the width of the steps, as was already mentioned. One can certainly argue with the level of the differences recorded for the ankle joint in this study, as none of these authors has not recorded such significant differences. Bearing in mind hypothetical variations in motor strategies of both forms of locomotion and the postulated necessity of learning this type of gait, the recorded results are likely to be obtained. Of course, the mentioned thesis may be used for further investigations, especially as the importance of the ankle joint for locomotion is following from the fact that it is regarded as one of gait determinants [33].

5. Conclusions

The analysis of the results of man's natural (free) walking at the speed of 5 km/h, both on the ground and on a treadmill, allowed a few specific proposals to be formulated:

1. The spatio-temporal analysis of both gait variants (overground and treadmill) showed that 5 out of 8 parameters differed significantly ($p < 0.05$), but the differences were not large – they did not exceed 6%.

2. Qualitative and quantitative differences in angular parameters in the sagittal plane during walking on the ground and on a treadmill were the greatest in the ankle (12° difference – AF_{PSW}, $p < 0.001$), while the slightest in hip joint (4° difference, HE_{TST}, $p < 0.05$). The influence of the surface on knee angular value is of intermediate level of the previously mentioned (3° difference – KF_{ISW}, $p < 0.01$).

3. The differences in the movement on the treadmill and on the ground were revealed during angular changes of the main joints of lower limbs. The type of the surface used affected the gait range of motion, the instantaneous values of angles and dynamics of these values.

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