Abstract:

Aim. The aim of the work is comparative assessment regarding the basic parameters of locomotive biomechanics on various surface conditions.

Materials and methods. The study involved $n=18$ adolescents. The condition for inclusion in the study was regular sports training. The test was conducted at SMS [School of Sports Championship] Mrągowo, April 2019, in the field environment, on a stable surface (concrete surface) and unstable surface (beach volleyball court). The test was performed using a body composition analyser and a diagnostic system testing gait and balance. The obtained results were analysed via statistical methods.

Results. The level of statistical significance was assumed at $p<0.05$. In the conducted tests it was found that the type of the ground is significant for certain gait parameters, gait speed ($p = 0.003$), gait rhythm ($p = 0.02$), step length ($p = 0.007$), step height ($p = 0.002$) and the length of the left ($p = 0.0006$) and right step ($p = 0.024$) on unstable surface conditions were statistically significantly different from gait in stable conditions.

Conclusions. All statistically significant parameters may affect the implementation of training assumptions. These identifiers can arouse interest from the perspective of creating an exercise plan with emphasis on these factors. Further in-depth analysis of gait in various conditions, to recognise gait mechanics in unstable conditions, may contribute to the recognition of many aspects of human life, from sports to rehabilitation and physiotherapy.

Introduction

A person can move in difficult conditions, e.g. uneven area, modifying his/her preferred walking pattern, e.g. step length, width or speed. Growing behavioural and neuroimaging evidence suggests that the ability to modify preferred step patterns requires an extension of cognitive resources [1].

The analysis of gait parameters is a very important tool for its assessment. Various aspects of gait are examined, including: length and frequency of steps, analysis of the support and swing phase and course of ground reaction forces. In clinical practice, quantitative and objective methods of gait analysis are used, based on physical measurement, description of measurable features and their assessment characterising human locomotion. Temporal-spatial gait as well as kinetic parameters and muscle activity during gait are assessed.

Locomotion is the result of coordinated activity of about 10 muscles covering many of the joints. According to Blaszczyk [2], gait is a cyclical physical activity, which means continuous repetition of specific coordination patterns of the lower limbs and other parts of the body. Cyclic and rhythmic variable movements of the limbs and trunk are aimed at moving the human centre of gravity forwards, which is to cause the displacement of man in space. In normal gait, there are two consecutive phases: the support phase and the transfer phase.
However, position-specific analyses, e.g., maximal training on unstable surfaces compared to stable ones. Adolescents and adults were found in favour of strength and balance in healthy adolescents, adults and the elderly. It was found that children in the mid-childhood range are able to significantly improve exercise performance. However, children under the age of 9 have worse mobility compared to older children and adults, whose difference in the level of manifestation becomes more pronounced as the task complexity increases [4]. Bisi and Stagni [5] suggest that during puberty, body height affects the variability, fluidity and regularity of gait, but not its stability. Peripheral changes of the body, occurring in adolescents, influence the manifestation and efficiency of gait. On the other hand, in gait control, young, healthy, developing individuals are able to cope with these modifications, maintaining a level of gait stability compared to their more slowly growing peers.

Lago-Fuentes et al. [6] analysed the effect of strength training on stable and unstable surfaces regarding a reduction in injury occurrence. Granacher et al. [7] conducted a study in which the impact of strength training, in relation to stable and unstable surfaces, on health and related physical fitness in healthy school-children, was determined. Strength training has been shown to be an effective means to strengthen trunk muscle strength and physical fitness indices in adolescents. It is noteworthy that cross-sectional studies have revealed that the inclusion of unstable exercise components resulted in an increase in trunk muscle activity, and thus, provided potential additional training stimuli to improve its efficacy. Thus, the use of unstable surfaces during strength training can bring many benefits to the body. However, the effects of strength training using unstable surfaces remain not fully recognised in adolescents. Behm et al. [8] also performed a systematic literature review and meta-analysis to investigate the effect of strength training on unstable surfaces. The main conclusions of the analysis were that strength training on an unstable surface is an effective way to improve muscle strength, power and balance in healthy adolescents, adults and the elderly. Moreover, higher strength and balance metrics for adolescents and adults were found in favour of strength training on unstable surfaces compared to stable ones. However, the position-specific analyses, e.g., maximal strength, did not show benefits of strength training on unstable surfaces compared to stable ones.

Increasing surface instability during maximal exercise (squat) usually maintains muscular activity of the lower limbs and trunk muscles, although baseline strength is reduced. This suggests that unstable surfaces for squats may be beneficial in rehabilitation and as part of periodic training programmes, because similar muscle activity can be achieved with reduced loads [9]. However, Inoue et al. [10] suggest that fatigue of lower limb muscle groups may affect their balance function. Further analysis indicates that fatigue in the extensors and flexors of the hip and knee, as well as the muscles around the ankles, significantly reduces the function of balance. In studies, it is suggested that hip extensor muscle fatigue is associated with a decrease in lower limb balance function among healthy young adults, thus, it would be beneficial to adopt a balance training programme that focuses on strengthening the hip extensors.

As a result of the analyses, it was noticed that the inclusion of surface instability in exercises strengthening the spinal muscles caused an increase in the activity of the trunk muscles. The research problem of the study is the question:

*Are there statistically significant differences in the structure of movement on stable and unstable ground conditions among athletes who are active in adolescence?*

The aim of the study is to compare the basic parameters of locomotion biomechanics regarding different ground conditions. An additional objective is to determine the relationship between variables and indicate the structure of the movement structure built from the parameters analysed in the compared ground conditions. The research allows for the continuation of analyses and obtaining information on the qualitative and quantitative biomechanical parameters of the work of lower limbs and feet on an unstable surface. The authors hypothesise that the parameters of locomotion in active athletes, in stable and unstable ground conditions, differ significantly.

**Materials and methods**

The study involved n=18 adolescents. The condition for inclusion in the study was regular sports training. The test was carried out at the Mrągowo School of Sports Championship in April 2019, in field conditions, on a stable (pavement) and unstable surface (beach volleyball court). The test was carried out in footwear, it consisted of a single passage of a 15-meter section on stable ground and a 15-meter section on unstable ground.
The study was performed using the *InBody* 270 body composition analysis device and the Wiva® Science diagnostic system using the *BioMech Studio* program. The obtained results were analysed with the *Statistica* 13 program.

The research consisted in identifying the assumed differences within the same gait parameters on a stable and unstable surface.

**Results**

Tested components: speed, rhythm - as the number of steps taken per minute, length of the left and right steps - the distance between the left and right heel stroke as well as the right and left heel stroke, as a percentage of the entire gait cycle, gait cycle duration - the time between two successive heel strokes of the same foot, the duration of the left and right step - the time between the left and right heel strokes, as well as the right and left heel, support time – percentage reference to the entire gait cycle of the support phase, as the average of the data obtained for both feet, left and right support time – percentage reference to the entire walking cycle of the left foot and right foot support phase, transfer time - percentage reference to the entire gait cycle of the transfer phase, as the average of data obtained for both feet, left and right transfer time – percentage reference to the entire gait cycle duration of left and right foot transfer phase, double support duration – percentage reference to the entire gait cycle of the support phase duration for both feet, and single support – percentage reference to the entire gait cycle of the support phase for one of the feet. In the table below, all the detailed measurements are presented for each participant: S – on a stable ground, and N – on an unstable surface.

The conducted research depends on finding significant statistical differences, while measuring the same gait parameters on a stable and unstable surface, and revealing the differences, if any. Below are detailed examples of statistically significant results.

This chart graphically presents gait parameters depending on speed in relation to the two types of surfaces used in the experiment (stable and unstable). When analysing the presented results, it should be noted that in terms of subjects’ movement speed, a statistically significant difference ($p = 0.003$) in relation to the unstable ground was

![Box plot](image_url)

**Tab. 1. Numerical characteristics of the examined group**

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>Body height (cm)</th>
<th>Body mass (kg)</th>
<th>BMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>14.44</td>
<td>171.72</td>
<td>61.14</td>
<td>20.48</td>
</tr>
<tr>
<td>SD</td>
<td>1.86</td>
<td>11.93</td>
<td>13.29</td>
<td>2.42</td>
</tr>
</tbody>
</table>

**Fig. 1. Differences in the value of the measured gait speed parameter on a stable and unstable surface**

source: own research
noted. Therefore, it should be stated that the walking speed on a sandy surface is of importance regarding the general technique of human movement in unstable conditions.

There are also differences in the average gait speed, but they are not statistically significant.

Analysing the box plot graph regarding the gait rhythm characteristics, a statistically significant difference was found at $p = 0.017$. This may indicate that the walking rhythm is very important when moving on an unstable surface. As a result of the statistical analysis,

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**Fig. 2.** Differences in the parameters of the gait rhythm, tested on a stable and unstable surface. Source: own research

**Fig. 3.** Differences in the values of the step length/height parameter, tested on a stable and unstable surface. Source: own research.
Fig. 4. Differences in the values of the step length/height parameter, tested on a stable and unstable surface

Source: own research

Tab. 2. Assessment of statistical significance for selected parameters of the BioMech Studio test regarding correctness of participants’ gait on a stable and unstable surface

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>Std. dev.</th>
<th>Significant</th>
<th>Difference</th>
<th>Std. dev. difference</th>
<th>t</th>
<th>p</th>
<th>Confidence -95.000%</th>
<th>Confidence +95.000%</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-Left step length: m</td>
<td>0.83</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Left step length: m</td>
<td>0.78</td>
<td>0.11</td>
<td>18</td>
<td>0.05</td>
<td>0.05</td>
<td>4.24</td>
<td>0.0006</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td>S-Right step length: m</td>
<td>0.83</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Right step length: m</td>
<td>0.78</td>
<td>0.10</td>
<td>18</td>
<td>0.04</td>
<td>0.07</td>
<td>2.49</td>
<td>0.024</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>S-Left step duration: %</td>
<td>0.45</td>
<td>1.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Left step duration: %</td>
<td>9.73</td>
<td>1.21</td>
<td>18</td>
<td>0.71</td>
<td>2.37</td>
<td>1.28</td>
<td>0.22</td>
<td>-0.47</td>
<td>1.89</td>
</tr>
<tr>
<td>S-Right step duration: %</td>
<td>9.79</td>
<td>1.56</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Right step duration: %</td>
<td>9.27</td>
<td>1.27</td>
<td>18</td>
<td>-0.48</td>
<td>2.50</td>
<td>0.82</td>
<td>0.42</td>
<td>-1.73</td>
<td>0.76</td>
</tr>
<tr>
<td>S-Support duration [% gait cycle]</td>
<td>1.86</td>
<td>1.38</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Support duration [% gait cycle]</td>
<td>1.79</td>
<td>0.99</td>
<td>18</td>
<td>0.06</td>
<td>1.64</td>
<td>0.16</td>
<td>0.87</td>
<td>-0.76</td>
<td>0.88</td>
</tr>
<tr>
<td>S-Support duration [% gait cycle]</td>
<td>6.14</td>
<td>1.20</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>N-Transfer duration [% gait cycle]</td>
<td>6.38</td>
<td>1.06</td>
<td>18</td>
<td>-0.22</td>
<td>1.66</td>
<td>0.57</td>
<td>0.57</td>
<td>-1.05</td>
<td>0.80</td>
</tr>
<tr>
<td>S-Left support duration [% gait cycle]</td>
<td>1.80</td>
<td>1.30</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Left support duration [% gait cycle]</td>
<td>1.70</td>
<td>1.52</td>
<td>18</td>
<td>0.10</td>
<td>1.68</td>
<td>0.26</td>
<td>0.80</td>
<td>-0.73</td>
<td>0.94</td>
</tr>
<tr>
<td>S-Right support duration [% gait cycle]</td>
<td>1.91</td>
<td>1.94</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Right support duration [% gait cycle]</td>
<td>1.89</td>
<td>1.04</td>
<td>18</td>
<td>0.02</td>
<td>2.55</td>
<td>0.04</td>
<td>0.97</td>
<td>-1.25</td>
<td>1.29</td>
</tr>
<tr>
<td>S-Left transfer duration [% gait cycle]</td>
<td>6.13</td>
<td>0.78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Left transfer duration [% gait cycle]</td>
<td>6.43</td>
<td>1.69</td>
<td>18</td>
<td>-0.30</td>
<td>1.58</td>
<td>0.81</td>
<td>0.43</td>
<td>-1.10</td>
<td>0.49</td>
</tr>
<tr>
<td>S-Right transfer duration [% gait cycle]</td>
<td>6.14</td>
<td>1.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Right transfer duration [% gait cycle]</td>
<td>6.29</td>
<td>0.99</td>
<td>18</td>
<td>-0.15</td>
<td>2.60</td>
<td>0.24</td>
<td>0.82</td>
<td>-1.44</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Source: own research
it can be found that in terms of rhythm, subjects should undertake training to bridge these differences.

An extremely important gait parameter, which results from publicly available literature, is step length. As a result of the analysis, it turned out that with respect to numerical values, statistically significant differences in the length of the step were observed at the level of $p = 0.007$. It should be noted that the length of the step varies depending on the stability of the ground.

Statistically significant differences in step height at $p = 0.002$ were also revealed in the study. The obtained results are not surprising, because while walking, gait is more difficult when rebounding off a soft (unstable) ground than under normalised (stable) conditions. Such results indicate that the training process of people actively practicing sports should include exercises on unstable surfaces. Step height analysis can lead to the belief that the obtained values are important for the efficacy of human movement in such conditions.

In Table 2, all remaining parameters obtained as a result of the study are summarised. As it may be concluded from the numerical analysis of the above table, statistically significant differences were obtained regarding the following parameters: left step length ($p = 0.0006$), as well as the length of the right step ($p = 0.024$). Other obtained values regarding duration of the left step, right step duration, support and transfer phase duration, left and right support duration as well as left and right transfer phase duration, did not reveal statistically significant differences.

**Discussion**

Locomotion using two limbs requires a kind of sense of balance and is often referred to as controlled falls - if we do not properly place one foot in front of the other, we will experience a fall. The method of locomotion used by man requires a high, straight and very unstable structure maintained in balance when supported by only one foot. We walk to move in space, to move our head and hands and other places, to fulfill our needs and desires. This seemingly simple activity requires the involvement of the central and peripheral nervous systems, internal planning and the ability to predict actions and reactions. It uses the interaction of many other senses developed millions of years ago [11]. It is believed that since man the upper limbs from the need to support posture in the process of phylogensis freed and became a bipedal, it is a constant struggle to maintain a “safe” body posture in static and dynamic conditions. Full extension in the knee and hip joints, a reduction in the support plane and a shift in the centre of gravity of the body, reduced the limit of stability. This forced the development of a number of new neurofunctional mechanisms, such as postural reactions and strategies for maintaining body balance based on the proper functioning of the vestibular sight organs, as well as proprioceptive sensation. Maintaining the activity of nervous processes towards continuous learning and improving the balance function lasts throughout human life [12].

All research, gait definitions, experiments, explanations, etc. that we have known for years are carried out on a flat surface, a perfectly even surface, so that nothing from the outside would disturb the stable position, balance or concentration of the examined person. Monographs and scientific articles primarily focus on issues related to gait analysis under stable conditions. There is a lack of information on the subject of gait analysis under unstable ground conditions. It is important to understand how people adjust their gait while walking in real conditions with variable surface characteristics [13]. In this study, the authors focus on comparing gait on a stable and unstable surface – sand, in young athletes using the Wiva® Science device. The tested parameters showed differences when walking on both grounds, however, speed [m/min], rhythm [steps/min], step length [m], length/height of the step [%], length of the left step [m] and right step [m] turned out to be statistically significant when carried out in an experiment on an unstable ground. The duration of the left and right steps [%], the duration of the left and right supports [%/gait cycle] and the duration of the right and left transfers [%/gait cycle] showed no significant effect on gait changes on unstable ground.

Many researchers conduct experiments on unstable surfaces, as among others: unstable shoes, gym balls, all kinds of mats with unstable surfaces, and even obstacle courses. Referring to such studies, it turns out that unstable surfaces have a very positive effect on the body during the rehabilitation of people after stroke or even when rehabilitating the lower limbs.

Previous research, in contrast to the concepts of the experiment presented in this study, concerned an unstable ground in relation to therapy among people with gait and postural dysfunctions. The studied impact of trunk rehabilitation using unstable support surfaces compared to stable ones on static and dynamic balance after stroke, proved to be better than stable surfaces, improving static and dynamic balance. Physiological balls, airbags, balance pads and unstable plates are suitable supports for increasing balance during stroke rehabilitation. Trunk training was provided as an additional therapy or without conventional therapy. The implementation of unstable support at an early stage of rehabilitation may be more beneficial [14].

In another experiment, Chan and Fu [15 p. 781] used a rehabilitation programme that included core-muscle, lower limb strength and balance training by using the
BOSU ball as a training tool. However, the vertical jump, 30-meter sprint run and dynamic balance (Star Balance Test, SEBT) tests were carried out before and after the training programme. For test analysis, the t test was used for dependent samples at the level of \( p = 0.05 \). It turned out that 6 weeks of training on unstable ground can improve dynamic balance, vertical jump height and speed in the 30-meter sprint for women playing football. The obtained results differ from those obtained as a result of the experiment conducted for the purposes of this study.

The authors, as in this study using Wiva® Science, also focused on the height parameter of obtained heights, among others, of the step. The inclusion of exercises on unstable ground conditions in the routine training of young women in football is important for the development of sports fitness.

Poremba, Makubuya and Muwonge [16] conducted a study assessing the impact of 4 weeks of training on an unstable surface using the PRIMFIT product in combination with manual physical therapy for a sprained ankle. The subject showed clinically and statistically significant improvement in all gait and temporal parameters measured by the OPTOGAIT. In addition, the patient showed increased ankle mobility, reduced swelling and eliminated pain after completing 4 weeks of rehabilitation 2 two weeks of physical therapy and individual rehabilitation. The improvement in left leg (\( M = 1.1; \text{SD} = 7.7; \) \( r = 0.932, p = 0.021 \) and right leg gait (\( M = 1.7; \text{SD} = 8.2; \) \( r = 0.924, p = 0.025 \), was significant. The results obtained in this study are similar.

Unstable footwear designs are popular as training devices that enhance human neuromuscular control, and in many studies, their impact on gait parameters is assessed in comparison to conventional footwear designs. However, research on the variability of gait measures, while walking in unstable shoes, are minimal. Therefore, the purpose of the study by Khoury-Mireb et al. [17] was comparison of variability in gait measures between stable and unstable footwear configurations, combined with kinematic and kinetic changes. Significantly reduced gait variability in the feet, ankles and arms when walking in a unique unstable shoe was demonstrated in the study. The results also showed a simultaneous increase in the variability of the dorsal angle in the transverse plane, which can be used to maintain adaptability and flexibility, and thus, maintain dynamic stability. The experiment, being the basis for obtaining the results of this study, was also aimed at indirect analysis of neuromuscular control, but the means to achieve this goal was not the use of an unstable shoe, but the use of sand on a beach volleyball court.

The results of the study showed that athletes who regularly exercised on variable-sensitivity surfaces (water, ice, wheels) were characterised by different posture stability than athletes performing other sports. Qualified athletes have been shown to demonstrate better balance compared to non-athletes [18]. Athletes were also the research subject of this study, and the research objective was of a similar nature, as the aspect of length, rhythm and speed of gait in unstable conditions were analysed, the parameters of which proving to be statistically significant and indirectly affecting the level of balance.

The research by Yoo, Jeong on Lee [19] on the effect of trunk stabilising exercises using an unstable surface on the structure of the abdominal muscle and balance in stroke patients, showed improved internal oblique and transverse muscles of the abdomen and the ability to maintain balance. These results suggest that trunk exercises on an unstable surface are useful for patients after rehabilitative stroke. According to Behm, Colado [20], physiotherapists should consider resistance training involving the use of unstable surfaces and devices as a progressive element of rehabilitation training programmes which can start with balance training (no load), then promotion to resistance training challenges for maintain balance, which requires the use of surface instability and a device for training ground resistance with the possibility of increasing loads and intensity. The research results in the presented work focused on gait analysis. Seeing the statistically significant differences in the studied parameters of the lower limbs during walking and the results obtained by the authors of the experiment, it can be stated that the effectiveness of training on unstable ground conditions has a greatly positive effect on the human body. Bang, Shin, Noh and Song [21] showed that unstable surface training improved walking ability and suggested the use of unstable surface training for clinical rehabilitation. The improvement of the ability to walk in stroke patients increases the possibilities of independent living and social activity. The results seemed to indicate an improvement in dynamic balance and stability. Unstable surface training with the use of a treadmill is a useful intervention for dynamic balance and walking resistance improvement. Conducting a review of literature, it became apparent that not only studies conducted among healthy individuals show a beneficial effect on the human body, but also in people after stroke.

**Conclusions**

- Significant differences were found in the values of the walking speed parameter, under different ground stability conditions. This statement indicates the need to include specialised measures related to the starting conditions under specific conditions of surface stability.
- Assessment of the reduction in measurement quantities, the length of the steps in unstable ground condi-
tions, is important in relation to gait stability. While walking on sand, a decrease in step length compared to the stable surface was noticed. This may be due to weakness of the examined muscles, or partly due to difficulties in maintaining balance while burdening one leg (this remains a subject of further research considerations).

- The duration of the support and transfer did not change at a statistically significant level while walking on unstable compared to stable ground.
- The obtained results may affect the implementation of training assumptions, because among all of the examined parameters, statistically significant differences were revealed regarding speed, rhythm, length and height of the steps.
- Further in-depth gait analysis should be conducted to identify its mechanics in unstable conditions. This can affect many aspects of human life from sports activities to rehabilitation and physiotherapy.

References:


Author for correspondence
Jarosław Jaszczur –Nowicki
E-mail: j.jaszczur-nowicki@uwm.edu.pl
ORCID: 0000-0001-5256-1406

Joanna M. Bukowska ORCID: 0000-0003-0729-7292
Marcin Krawczyński ORCID: 0000-0002-8515-234X