

Assessment of gait stability and preferred walking speed in virtual reality

PIOTR WODARSKI^{1*}, JACEK JURKOJC¹, JACEK POLECHOŃSKI², ANDRZEJ BIENIEK¹,
MIŁOSZ CHRZAN¹, ROBERT MICHNIK¹, MAREK GZIK¹

¹ Silesian University of Technology, Faculty of Biomedical Engineering, Department of Biomechanics, Gliwice, Poland.

² Institute of Sport Sciences, The Jerzy Kukuczka Academy of Physical Education in Katowice, Katowice, Poland.

Purpose: Analysis of human gait as well as diagnosis of human locomotion organ should always be conducted with velocity of gait equal to Preferred Walking Speed (PWS). The literature review shows that the PWS value is not the same in real and virtual environment. The aim of this study was to determine PWS values in both environments and to specify values of parameters used in equations enabling PWS calculations on the basis of lower limb length. *Methods:* Research-related tests involved 40 subjects walking on the treadmill and wearing HMD goggles. The spatial scenery made participants feel like during a walk in the park. The tests included measurements of displacements of the COP, allowing for the calculation of the Lyapunov exponent and Floquet Multiplier. Both coefficients were used to identify stability at various gait velocities. *Results:* The analysis revealed that the PWS in relation to gait on the treadmill with VR was lower than the PWS without VR. The final stage of research involved the determination of new values of coefficients of the formula enabling the identification of the velocity of comfort of gait in VR. *Conclusions:* Obtained results proved that PWS in real and virtual environment are different. The lower values were obtained for measurements in VR. On the basis of these results, value of the “*a*” coefficient, used in PWS calculations on the basis of lower limb length, was re-determined. The new value makes it possible to assess PWS for gait conducted on treadmill in virtual environment, what can be very important in gait evaluation.

Key words: gait stability, gait on treadmill, preferred walking speed, gait variability

1. Introduction

The application of Virtual Reality Technology to rehabilitation of a motor is nowadays a common practice [9]. This technology is used to make the process of rehabilitation more attractive as well as to motivate subjects to perform repetitive as well as labour- and time-consuming exercises [5]. The world of 3D graphics enables the introduction of visual disorders into the system, enhancing the diagnostic potential of spatial projection systems. While standing or walking on the treadmill in front of a wall with a 3D image or wearing 3D projection Head Mounted Display (HMD) system,

the subject is partially isolated from the outside world, which could affect their standing or gait stability [8], [18]. The above-named stability is often defined as the ability of system to respond to perturbation from our environment or from within our own bodies that influence our ability to move [2], [12], [15].

The primary objective of tests concerning the assessment of gait variability and stability is to prevent the loss of balance, which may result from disease of the nervous or musculoskeletal systems. The lack of ability to regain balance may lead to a fall which could end up in an injury or disability [2], [6], [7], [15], [18]. It was demonstrated that the risk of falling is the lowest when the velocity of the treadmill is consistent with

* Corresponding author: Piotr Wodarski, Silesian University of Technology, Faculty of Biomedical Engineering, Department of Biomechanics, ul. Roosevelta 40, room 125, 41-800 Zabrze, Poland. Phone: +48 512 998 000, e-mail: piotr.wodarski@polsl.pl

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the preferred walking speed (PWS), as well as gait analysis should be conducted while walking with habitual speed [2], [19]. An overview of research related to the aforesaid issue provided information that the PWS can be identified in two manners. The first method assumes the adjustment of the treadmill velocity to the subject's sense of comfort, i.e., the velocity is set to such value in which the subject can walk most comfortably [11], [15], [24]. The second manner assumes that the PWS is equal to comfort velocity V_{cf} determined on the basis of the limb length using dependence (1) [2], [10], [11], [18].

$$V_{cf} = a\sqrt{gl}. \quad (1)$$

In dependence (1.1) “ l ” stands for the length of the lower limb, “ g ” represents a gravitation constant of 9.81 m/s^2 . Coefficient “ a ” represents a proportionality coefficient of 0.42 [20] or 0.4 [16]. In addition, it can be stated that the walking speed closely corresponds to the walking stability. Research in this field was conducted, among others, by: Dingwel [2] and England [4]. Stability is defined as the ability of a system to achieve and maintain a constant value of measured signal. In the case of walking, stability is defined as the ability to maintain functional locomotion despite the presence of small kinematic disturbances or control errors [4]. Therefore, gait is not an activity in which the system can be said to be stable. However, the use of dependencies used to determine the stability of the system are extremely helpful during conducting gait analyzes. Studies on gait stability were conducted also by Jochymczyk-Wozniak [6], [7], Rosenstein [21] and in the case of robots were conducted by Spyrakos-Papastavridis [22]. Stability is usually assessed using values of standard deviation of the Lyapunov exponent [2], [4], [11], [21] or mean values of the Floquet Multiplier (FM) [11]. In the conditions of walking on a treadmill [2] and normal gait on a flat surface [4], [21], positive Lapunov coefficient values were obtained. Due to the aforementioned fact that human body during walking is not stable according to stability definition, movement analysis focuses on searching of the level of stability or, in other words, checking when the system reaches the smallest value of instability.

The stability proved to be the highest when walking on the treadmill at the PWS, with eyes open and without VR. The foregoing was confirmed by tests performed by Dingwell, Kang and Terrier [2], [11], [24]. It was the PWS in relation to which the lowest average standard deviations of the Lyapunov exponents and the closest to the values of FM were obtained. The increase or decrease of the velocity of the

treadmill reduces the repeatability of displacements of the centre of mass (CoM) in space, which affects the variability of gait and reduces its stability [2], [4], [24]. The results of related tests revealed that the PWS is the speed at which the highest stability is obtained and is often referred to as the velocity of comfort (V_{cf}). Through dependence numbered (1.1), V_{cf} is related to the length of the lower limb [4], [15]. In the above-named dependence, a parameter determined empirically is coefficient of proportionality “ a ”, identified on the basis of tests involving healthy individuals. By applying a similar method based on the assumption of equality between the PWS and V_{cf} it is possible to determine whether in relation to the PWS in the VR as well as in relation to the obtained values the highest stability is obtained. In addition, it is possible to calculate coefficient of proportionality “ a ” and compare it with the coefficient of proportionality “ a ” determined through the analysis of reference publications and concerning gait without the use of VR.

It should also be noted that examined individuals wearing 3D goggles do not have a visual contact with the real surroundings. Due to that they feel less comfortable and, as a result, their gait velocity is reduced. The foregoing was confirmed, among other things, by tests performed by England and Granata [4], Menegoni et al. [17], Wong et al. [25]. It is essential to formulate a hypothesis stating that gait in the VR is characterised by different velocity of comfort than gait in real environment and, because of this, it is necessary to determine a new coefficient of proportionality “ a ” to calculate the velocity of comfort in virtual environment. This knowledge can be crucial while the rehabilitation's procedure and exercise's parameters are determined. It also seems justified to identify the velocity of comfort and the PWS for gait using the 3D projection of virtual images in relation to specific graphic sceneries. Such tests will supplement the previously acquired knowledge by a method enabling the correction of the calculation of the velocity of comfort (V_{cf}) of gait using the Technology of Virtual Reality (VRT). Therefore, the main aims of the study were to: determine values of Lyapunov exponent and the Floquet Multiplier for group of healthy people, for different velocities of gait both for real and virtual environment, determine PWS velocities in real and virtual environment, on the basis of obtained Lyapunov exponent and the Floquet Multiplier and determine new value of “ a ” parameter for gait in VR to make it possible to calculate PWS for gait in VR on the basis of length of lower limb.

2. Materials and methods

Study group

The study group included of 40 participants (20 females and 20 males) aged 21.75 ± 1.11 , with an average height of 174 ± 8.04 cm and an average weight of 68.08 ± 12.44 kg. None of the participants had had a history of an extreme lower limb injury or suffered from motor system dysfunctions or balance disorders.

Approval

This study was previously approved by the Ethics in Research Committee of the Academy of Physical Education in Katowice (protocol number 11/2015).

Experimental procedure and the analysis of results

The study was performed on a measurement treadmill (WinFDM-T, Zebris) using a safeguard harness system not affecting the movements of a tested person. The participants were wearing the HMD system – Oculus DK2 goggle – used for displaying a 3D scenery designed as virtual reality. The scenery is presented in Fig. 1A, whereas the tests along with the measurement stand are presented in Fig. 1B.

The test was composed of 2 stages during which the participant was walking on the treadmill. Before the measurement, each participant was informed about the test procedure.

At the first stage of the test, participants were walking on a treadmill with Oculus goggles on their heads. Goggles were used to present 3D graphical scenery, prepared as a path with growing trees on the sides, which was moving, giving the illusion of walk-

ing along this path. The speed of movement of the surroundings could be adjusted and was set equal to the speed of the treadmill. In such conditions, the examined person had to determine what speed is the most comfortable for them (procedure was in details described in previous publications [2], [11], [15], [23]). This velocity was treated as PWS. For such, determined velocity, the lower and higher velocities were calculated, as the multiplication of this velocity by 0.8, 0.9, 1.1, 1.2 and 1.4.

In the next step for all these velocities, 6 measurements were conducted in random order. Each of them lasted for 30 second. A participant was to walk on a treadmill in virtual environment. For each test, the consecutive positions of COP were measured. Then, the obtained results were used to determine the highest stability in relation to gait velocity. To this end, on the basis of the course of COP, the Lyapunov exponents along with their standard deviations, as well as the Floquet Multipliers (FM), were calculated. They were identified individually for each test and each participant.

Calculations of the above-described indices were carried out in the MATLAB environment using software prepared by authors of this article. Obtained results made it possible to assess gait stability for all research conditions. All analyses were conducted on the basis of the procedure described by Dingwell [2], Kang [11] and Terrier [24]. These authors stated that the greatest stability can be obtained for the velocity equal to PWS. This assumption made it possible to determine PWS in virtual reality conditions, assuming that Preferred Walking Speed was reached when the gait was most stable. Then, in the next step of calculations, new values of “*a*” parameter were determined for each person by means of (1) equation.



Fig. 1. A – Three-dimensional graphic scenery displayed during tests, B – test and the measurement stand

Methodology of Lyapunov exponents and Floquet Multipliers calculation

Similarly to the studies [4], [12], [14], [22], in the first stage of calculations of the Lyapunov index, m -dimensional state-space reconstruct was determined from a single time series of COP trajectory reconstruction. This operation was performed by obtaining m -dimensional space from one dimensional time series of COP trajectory, according to Takens's theorem. In the next step each point from COP trajectory was delayed m times by J points in time series. In this way the following \mathbf{X} matrix was created (dependence 2),

$$\mathbf{X}_i = (x_i, x_{i+J}, \dots, x_{i+(m-1)J}), \quad (2)$$

where x is COP position component and i is point indexer from 0 to length of COP trajectory. The time delay J is computed as minimal time lag needed to obtain less or equal then $1-1/e$ autocorrelation value from signal. The next step is to find for every point in time series the nearest neighbour point (using Euclidean distance) in one of next gait cycles and compute distance between these neighbours during whole trial according to dependence (3),

$$d(j, i) = |X_{(j+i)} - X_{(j'+i)}|, \quad (3)$$

where j is number of first point for each step on COP trajectory and j' is index of nearest neighbour of j point. Lapunov exponent can be approximated using least-square fit to the line (described by dependence (4)) between 0 and 1 gait step, it is λ_S , and between 4 and 10 gait step, it is λ_L .

$$f(i) = 1/\Delta t \text{ mean}(\ln(d(j, i))) \quad (4)$$

The obtained in this manner Lyapunov index values λ_S and λ_L only provide information about the stability of the system. They only determine whether the system under analysis is stable or not, they do not specify the degree of stability [1], [13], [14]. In relation to the conducted measurements it could be supposed that the analysis of gait based on the COP positions indicated short-term instability (λ_S). COP measurements during walking always show instability, as COP displacements do not follow a straight line [13]. Due to the aforementioned fact of the instability of the system, movement analysis looks for when the instability of the system is the smallest, or, in other words, when the system is closest to a state that can be considered stable, the level of this instability is determined by analysing the standard deviation of the Lapunov index.

Using the method described by Bisi and Kang [1], [11] the mean values of the FM were determined. In the first step of FM calculation the interpolation to 101 k -points of COP position in each gait cycle was calculated. That represents each of gait cycle percent. To calculate FM index, it was necessary to constitute the limit cycle trajectory (LCT) and it was done by averaging COP trajectory across every single gait cycle. The next step of the calculation was to create a matrix, called J -matrix according to dependence (5),

$$J = \frac{COP_{k+1} - LCT_{k+1}}{COP_k - LCT_k}, \quad (5)$$

where COP_k is value of COP position for k -point, LCT_k is value of limit cycle trajectory for k -point. Floquet multipliers were defined as eigenvalues of this J -matrix. If maximum FM were less than 1, then all small perturbations would shrink in next stride and system will remain stable. In this research, the FM index was calculated for all moments of time, but in stability assessment, according to Bisi [1] and Kang [11], it was decided to take only one moment corresponding to 50% of the gait cycle.

Statistical analysis

All calculated quantities were averaged for the entire group and then analysed in order to indicate statistically significant differences. The existence of normal distribution was examined by means of the Shapiro–Wilk test, the homogeneity of the variance was examined using the Levene's test and finally, the existence of statistically significant differences in the expected parameters were examined using Student's t -test for dependent samples and the ANOVA test for LARGER groups of parameters. The calculations were performed using the statistical software programme "Statistica" version 13.3.

3. Results

In Figure 2, mean vales of Lyapunov exponents λ_S and λ_L obtained for the entire group on the basis of measurement results received at the first stage of measurements are presented.

Statistical analysis revealed the lack of statistically significant differences between the values obtained in relation to parameters λ_S (ANOVA $p > 0.37$). However, in relation to parameter λ_L , it was possible to observe a significant increase in the mean value along

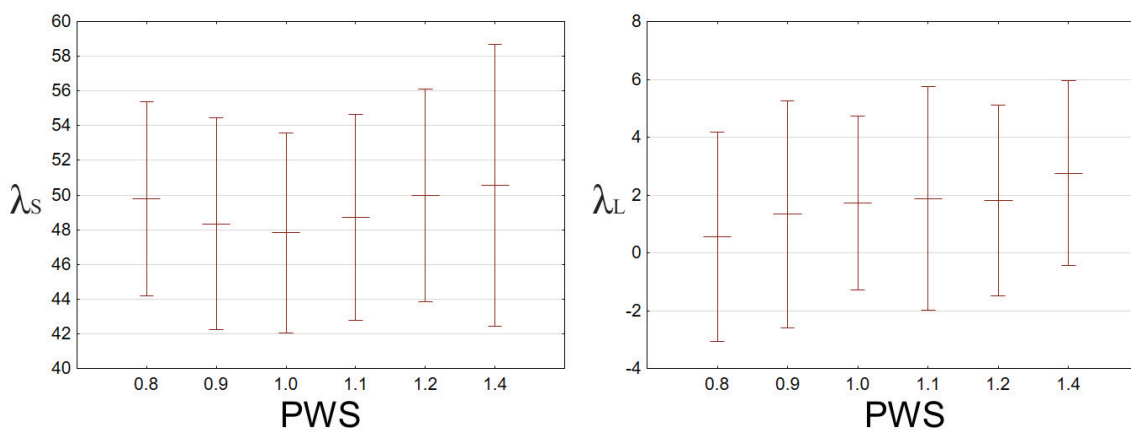


Fig. 2. Values of Lyapunov exponents λ_s and λ_L ; values related to determined multiplication factors of the PWS; whiskers indicate standard deviations

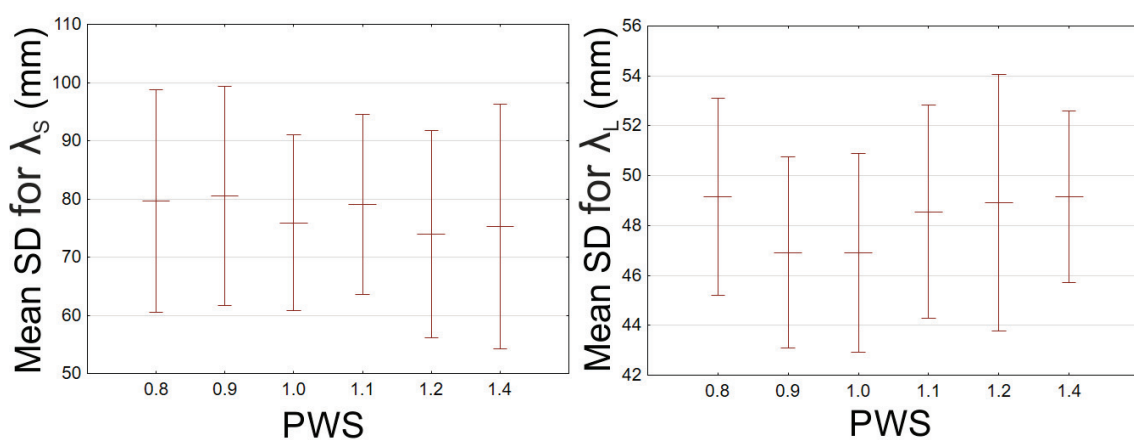


Fig. 3. Values of mean standard deviations in relation to Lyapunov exponents λ_s and λ_L calculated for each stride separately and averaged for each person separately and, afterwards, averaged for the entire test group. The values are presented before the process of finding the logarithm, being the final step of Lyapunov algorithm in relation to the determined multiplication factors of the PWS; whiskers indicate standard deviations

with an increase in the velocity of the treadmill (ANOVA $p < 0.1$).

In Figure 3, calculated mean values of standard deviations in relation to Lyapunov exponents λ_s and λ_L are presented. The above-named values were calculated in the same manner as in publication [2] – as standard deviations of the distance between the Lyapunov space trajectories in relation each stride separately. Afterwards, the aforesaid values were averaged in relation to each person. The next step involved the calculation of the mean value in relation to the entire group of test participants. The calculated mean values of standard deviations were presented as values before finding the logarithm, before the final step of the algorithm of Lyapunov calculations [21], which indicates significantly higher values on the vertical axis.

The statistical analysis revealed the lack of statistically significant differences between the mean values of standard deviation of λ_s parameters (ANOVA $p > 0.4$). In relation to mean values of standard deviation of λ_L

parameter, there were statistically significant differences between mean values (ANOVA $p = 0.0496$). The values related to 0.9 PWS and 1.0 PWS were statistically lower than the other values (*post hoc* $p < 0.1$).

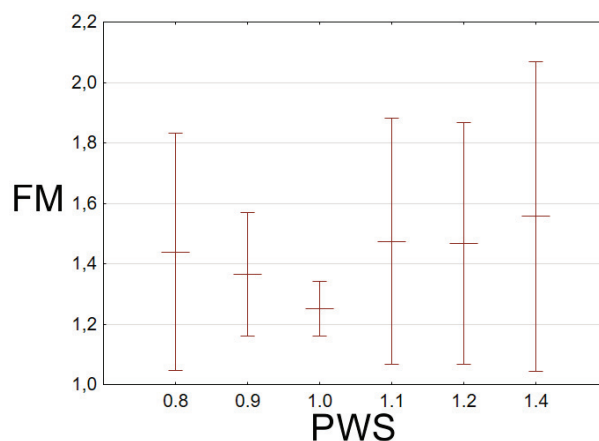


Fig. 4. Values of Floquet Multiplier; whiskers indicate standard deviations

In Figure 4, the values of the Floquet Multiplier (FM) averaged for the entire group are presented.

In Figure 5, the lower mean value of FM coefficient in relation to 1.0 PWS and a significantly lower standard deviation of the values are presented. The statistical analysis revealed the presence of significant differences between the mean values in relation to FM (ANOVA $p = 0.012$). The values between 0.8 PWS, 0.9 PWS and 1.0 PWS differ slightly (*post hoc* $p < 0.2$). The values obtained in relation to 1.1 PWS, 1.2 PWS and 1.4 PWS are statistically higher than 1.0 PWS (*post hoc* $p < 0.05$).

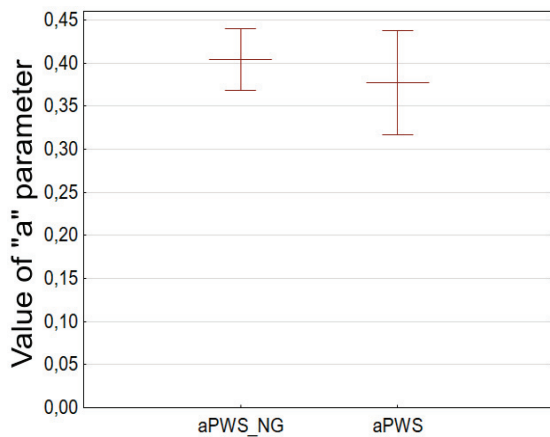


Fig. 5. Values of coefficients of proportionality "a" obtained in relation to PWS_NG (gait at the preferred walking speed and without 3D goggles) and PWS (gait at the preferred walking speed and with 3D goggles); the middle line represents the mean value, whiskers represent plus/minus standard deviation

The mean values of aPWS_NG were statistically significantly higher than the mean values of aPWS (Student's t -test $p < 0.00055$). The standard deviation was higher in relation to aPWS; the dispersion increased towards lower values.

4. Discussion

4.1. Lyapunov exponents and Floquet Multiplier (FM)

The analysis of the stability of participants walking at various velocities of the treadmill and being exposed to the disruption in the form of virtual scenery was based on the mean values of the standard deviations of the Lyapunov exponents. The obtained results did not reveal statistically significant differences between individual velocities of gait in relation

to the standard deviations of Lyapunov exponent λ_S , yet they revealed differences in terms of the standard deviations of Lyapunov exponent λ_L . The lowest values were obtained in relation to the velocity of comfort indicated by the test participants and in relation to 0.9 of the aforesaid value (Fig. 3). In accordance with the assumption adopted during such analyses, stating that the lower the mean value of the standard deviation, the more stable the gait [2], it could be assumed that the above-named velocities were related to the most stable gait. Assuming that observations made by Dingwell [2], Kang [11] and Terrier [24], stating that the highest stability of gait was obtained for the PWS, could be projected on the tests performed in the virtual reality, it could be concluded that the velocity determined experimentally was the actual velocity of comfort in relation to the test participants. The observations based on the Lyapunov exponent were confirmed by the analysis based on the Floquet Multiplier (FM, Fig. 4). In the above-named case, the differences between individual velocities were even more visible oscillating at ± 0.1 of the absolute value of the FM.

The obtained values of the coefficients related to gait with open eyes and in the VR revealed that the use of disruption in the form of the virtual environment reduced the mean PWS velocity. The foregoing could result from the test participants' awareness that the visible surroundings could not entirely be used as the reference point enabling the identification of the actual position of the body during gait. However, regardless of the reason, the above-named fact should be reflected when performing tests concerning the identification of the PWS. As was demonstrated, among others, by Kang [2] and Dingwell [11], the performance of measurements at velocities varying from V_{cf} leads to the deterioration of human posture stability. The foregoing results in the conclusion that the performance of tests concerning the stability of gait, and, consequently, enabling the performance of the diagnostics of disturbed ability to maintain balance, should be performed at velocities corresponding to the PWS. Therefore, it is necessary to identify the manner enabling the determination of the PWS in relation to tests performed in virtual reality.

4.2. Identification of the PWS in Virtual Reality

The tests based on gait stability identification made it possible to indicate what gait velocities corresponded to the PWS during tests involving the use of disruption having the form of the VR. Regardless of

the mean values presented in the figures contained in the article, the PWS was determined for each participant individually. This enabled the calculation of the mean value of coefficient “ a ” used in formula (1) to identify the PWS. As a result, it was possible to identify the approximate PWS on the basis of the length of the lower limb of a person tested using the treadmill and VR. In relation to gait with open eyes, the mean value of coefficient of proportionality “ a ” is identical with results obtained by authors of other research publications on this subject [2], [16], [24] and, as regards the performed tests, amounts to 0.404. Statistical analysis indicates the reduction of the mean value of coefficient to 0.378 in relation to gait performed under VR conditions. However, it is necessary to pay attention to the standard deviation and the dispersion of obtained values. The above-named quantities indicate that the use of formula (1) with the mean value of coefficient “ a ” does not always allow for the determination of the PWS. In extreme cases, such differences can be considerable. This conclusion also seems true when using the aforesaid calculations in tests performed with open eyes. For this reason, when performing the above-named tests, it seems important that dependence (1) along with determined coefficients “ a ”, identified both in relation to the real environment and virtual reality, should be treated as the initial point of studies to be followed by the determination of the velocity of comfort on the basis of individual impressions of a test participant.

5. Conclusions

The literature review on treadmill gait tests indicates that conducting such measurements requires adjusting the speed of the treadmill to the PWS of the subject. This allows for the use of standardized and objective methods to assess the kinematic and dynamic quantities describing human gait. According to our knowledge, there are many studies showing how to set such speed, but none of the studies so far included the walk combined with the projection of three-dimensional, virtual images. However, the use of VR in the rehabilitation of locomotion is becoming more and more popular what can be explained by new possibilities of gait assessment and treatment which can be expanded in VR conditions. In such procedure, patient, among others, can be immersed in an environment which can be created exclusively for her/his personalized rehabilitation.

The research and analyses contained in this work show that there are significant differences between the

PWS values determined in real and virtual environment with 3D goggle, what proved the thesis from the Introduction chapter, showing the necessity to determine new parameters in equations used to PWS determination in virtual environment.

The analysis of stability during gait, based on the theory taken from automatics and robotics and conducted by means of the FM and the Lyapunov exponent proved that the highest stability of gait was obtained for PWS, both with and without VR projection. In the cases of the lowest values of the long-term stability λ_L (determined from Lyapunov’s characteristics), standard deviation for the short-term stability λ_S as well as of FM were obtained.

The analyses revealed that the preferred walking speed in virtual reality was lower than for gait on the treadmill without the projection of VR. Therefore, the use of the dependence enabling calculation of PWS on the basis of lower limbs length had to be corrected – the new value of “ a ” factor had to be determined.

Assuming the equality between the PWS and V_{cf} , the “ a ” coefficient, used in PWS determination, can be calculated for the gait in VR and obtained values of this coefficient were lower for gait in VR, comparing to results obtained in real environment. However, both for gait in real and virtual environment, standard deviation of obtained “ a ” values is noticeable. Therefore, in our opinion, the calculations with the use of this coefficient should be connected with the following tests enabling more precise determination of PWS.

The conducted research shows that the process of automating the selection of the walking speed based on the anthropometric characteristics of the investigated is extremely difficult, while for walking in the real world it is possible to determine how the preferred walking speed depends on the length of the lower limbs. In contrast to 3D projection systems, the subject turns out to be more complicated. In the calculations of automated systems dedicated to the rehabilitation, it is necessary to consider many more parameters than just anthropometry.

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