Analysis of the Relationship between Selected Stability Assessment Indicators on The Example of Leaning out the Human Body from the Upright Position

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Abstract

The objective of this paper is to study the margin of stability when trying to lean out the body forward and backward. The centre of mass of the body, the velocity of the centre of mass and extrapolated centre of mass were calculated for four participants. The analyzed movement was recorded by using BTS Motion Capture system. Recordings, in which participants were unable to return to the upright position, were also observed. In these cases, it was verified the usefulness of extrapolated centre of mass for predicting the foot support area that enables maintaining the body balance. The relationship between the applied stability indicators and anthropometric parameters was determined. The preliminary results obtained confirm the validity of the use of selected parameters in tests and in assessment of the stability of the human body, and indicate the directions of further tests for a larger group of participants and other movement activities.

Keywords: postural stability, extrapolated centre of mass, foot support polygon, motion analysis system

1. Introduction

In the scientific literature on biomechanics, stability is understood as the body's ability to return to the balance after a temporary disturbance of this balance [1]. The balance is defined there as the state of the body, in which the sum of forces and forces moments acting on it equal to zero. In the case of human body motion when the foot support area changes, the balance is not maintained. During gait and other movement activities, unbalanced forces and moments of forces act on the human body.

There are many methods for assessing stability in the literature [2]. However, most tests are dedicated only to movement activities, in which the foot support area does not change, e.g., in the quiet standing test or when trying to lean out the body backwards or forwards. Recently, the researches on human stability in dynamic conditions with changing foot support area are relatively scarce. The development of a dynamic postural stability indicators is a difficult scientific problem that is not yet fully recognized and requires further research [3].

In papers [3-6], studies on stability under dynamic conditions are presented. The authors of article [6] agree that this is an issue that still requires intensive studies, the reason being the poor quality of earlier methods and the low accuracy of the results obtained so far. The results showed that stabilization time is a parameter, which is insufficient for dynamic stability assessment because scientists and doctors could not closely assess the global changes in postural stability during movement.

Paper [3] verified the accuracy and effectiveness of stability tests among participants with Myotonic Dystrophy. The research was conducted using such stability measures as: the modified Dynamic Gait Index (DGI) and limits of stability. These parameters can detect the instant preceding the loss of balance, after which the falls can occur during movement. Therefore, these measures are useful in estimating the risk of falling.

In order to examine human mobility with the modified DGI, the participant's ability to perform eight movement tasks is examined. These tasks include climbing stairs and overcoming obstacles while walking. The tests are carried out under the supervision of a qualified and clinically trained person, which greatly restricts the general use of this test method. The test result is obtained on a scale of 0 to 64 points. The result of 0 points means inability to perform any element of the test, while the result of 64 points indicates the lack of noticeable balance disorders. The stability assessment is based on three elements: time required to complete the task (0-24 points), deviations from the walking pattern (0-24 points) and the required level of assistance (0-16 points).

The stability limits test gives an overview of individual participant movements in four directions: forward, backward, right and left. The examined movements are related to the participant's ability to consciously shift the body mass centre to the stability limits and maintain a stable posture in these positions without losing balance, putting a step or falling. The mass centre displacement with respect to the support polygon formed by the human's feet is determined.

According to the paper [3], these parameters require further research on a greater number of participants in order to increase the accuracy and reliability of the results. The authors noticed a lack of correlation in the results of the limits of stability. The values obtained did not differ significantly between healthy people and participants with dysfunctions.

2. Description of the used stability indicators

Dynamic stability is defined as the kinematic relationship between the state of the body mass centre (i.e. its position and velocity in relation to the current support polygon) and the analytically determined area of stability [7]. Based on experimental research, it has been found that when the projection of the mass centre on the support plane (GCoM) lies in the area of the supporting foot, the body maintains stable posture. Going outside the area of the polygon creates additional moments of forces that affect the foot and contribute to the rotation of the foot on the border of the polygon, which can lead to a fall [7].

However, the above thesis needs to be completed. In order to correctly formulate the stability conditions in dynamic situations, the velocity of the mass centre should also be analyzed, as the tracking of the mass centre position only is insufficient [8]. Even if the projection of the body mass centre lies in the foot support area, it is possible that a person will not maintain a stable posture in the case when the vector of velocity of the mass centre is directed outside the support area. The reverse is also possible. If the projection of the mass centre is located outside the support polygon, and the velocity vector is directed towards the contour of the feet, the balance can be achieved. In the paper [8] the description of dynamic stability was carried out using the inverted pendulum model, in which the length of the pendulum has a constant value, equal to the distance between the ankle and the body mass centre.

Simultaneous analysis of the velocity and acceleration of the mass centre is possible due to the coupling of the above quantities into one parameter called extrapolated centre of mass (XCoM) [8-10]. The position of XCoM was defined as:

$$p_{\mathrm{XCoM}} = p_{\mathrm{CoM}} + \frac{v_0}{\omega_0}, \tag{1}$$

where p_{CoM} - the position of the mass centre, v_0 - velocity of the mass centre, and ω_0 is calculated from the following formula:

$$\omega_0 = \sqrt{\frac{g}{l}}, \tag{2}$$

in which g is the acceleration of gravity, and l is the length measured from the ankle of the examined person to the body mass centre (called the length of the pendulum). The length l is taken as a constant value [8-10]. However, Y. Koyama and co-authors [9] emphasize that this assumption, due to imposed simplifications, may in some cases be a source of errors. During some movement activities, e.g., descending the stairs, the human body as well as its mass centre lowers. This results in a shorter distance between the mass centre and the central point of the ankle.

A. L. Hof and co-authors [8] claim that in order to maintain the stability of the system, the XCoM must be located in the area that is marked by the support polygon defined by the feet. In a situation when the XCoM goes beyond the support polygon, the system becomes unstable and there is a risk of falling. To maintain a stable posture during movement, a person must change the support area by taking a step and placing the foot in the right place or by controlling the position of the mass centre by displacing the torso or upper limbs.

3. The aim and method of the study

The purpose of this work is an additional analysis of the XCoM. This study is a key element for further research, in which a description of typically dynamic issues is planned. The tests were carried out at the Poznan University of Technology in the Laboratory of Biomechanics. During the studies, the participants were leaning out their body forward and backward, and then returned to the starting position. Each of the four participants performed 10 repetitions. Movements were recorded using the BTS Motion Capture system.

The position of the global mass centre was calculated for each participant using the Clauser's method [11]. Then the mass centre was projected onto the ground and the distance of the mass centre ground projection (GCoM) from the polygon of feet support, also called base of support (BoS), was calculated (x_{GB}). The position of the XCoM was determined for each recording. In contrast to the method presented in the literature, the length l was calculated as the distance of the marker placed on the ankle to the current location of the mass centre. The length l is therefore not constant, but depends on the body position. Recordings, in which the participant was unable to maintain balance and took additional step or fell over, were also analyzed. In these cases, it was checked whether the foot was placed close to the calculated XCoM. The dependence of the XCoM on anthropometric parameters (e.g. BMI coefficient) was also analyzed.

4. Analysis of the results

Human's ability to lean out his body forward is much greater than the ability to lean out his body backwards. When leaning backwards, three participants were unable to move their mass centre beyond the foot support polygon, and in these cases $x_{GB} = 0$. The fourth participant obtained a non-zero value of this parameter only in 2 trials out of 10 performed tests with the maximum value being max. $x_{GB} = 0.012$ m. At a higher parameter value, the participant would fall or take an additional step.

Table 1 presents the participants results when trying to lean out the body forward. The empty spaces in the table correspond to either the occurrence of artefacts during recording or interpolation errors in the process of estimating the position of disappearing markers. The values, which were made bold text correspond to the trials, in which participants were unable to maintain a stable posture and had to change the foot support area. The Mean parameter in tables 1 and 2 was calculated only for trials, during which participants were able to regain balance (without bold values). The values of x_{GB} and the velocity of the body mass centre v_{COM} are read at the moment of the maximum forward lean of the human body.

Table 1. The values of the distance of the mass centre ground projection from the base of support (x_{GB}) and velocity of the mass centre (v_{COM}) during leaning forward

	Participant 1		**Participant 2**		**Participant 3**		**Participant 4**	
Record No.	x_{GB} [m]	v_{COM} [m/s]	x_{GB} [m]	v_{COM} [m/s]	x_{GB} [m]	v_{COM} [m/s]	x_{GB} [m]	v_{COM} [m/s]
1	-	-	0.059	0.134	0.011	0.042	0.048	0.051
2	0.072	0.06	0.024	0.019	0.010	0.072	0.045	0.048
3	**0.157**	**0.502**	0.054	0.164	0	-	0.061	0.087
4	0.055	0.011	0.047	0.186	0.012	0.068	0.067	0.065
5	0.029	0.051	0.015	0.103	0.001	0.075	0	-
6	0.045	0.028	-	-	0.016	0.02	0.015	0.094
7	0.034	0.035	0.016	0.059	-	-	-	-
8	-	-	**0.213**	**0.712**	**0.074**	**0.202**	0.047	0.332
9	**0.147**	**0.583**	0.056	0.123	0.033	0.068	**0.369**	**0.677**
10	0.017	0.027	0.071	0.153	-	-	-	-
Mean	0.042	0.035	0.043	0.118	0.012	0.058	0.04	0.113

Table 2 contains data computed using the XCoM. The margin of stability (MoS) was calculated, which is defined as the distance between the XCoM and the boundary of the support polygon. The value of MoS is measured at the instant of maximum leaning (as the parameter x_{GB}), whereas the max_{MoS} value is the greatest value of MoS measured during a single trial (in the time from the starting upright to extreme positions).

Table 2. The margin of stability (MoS) and its maximum value (max_{MoS}) during leaning forward

	Participant 1		**Participant 2**		**Participant 3**		**Participant 4**	
Record No.	MoS [m]	max_{MoS} [m]	MoS [m]	max_{MoS} [m]	MoS [m]	max_{MoS} [m]	MoS [m]	max_{MoS} [m]
1	-	-	0.094	0.101	0.015	0.019	0.051	0.062
2	0.077	0.085	0.029	0.043	0.017	0.024	0.054	0.058
3	**0.294**	**0.299**	0.076	0.109	0	0.015	0.066	0.079
4	0.054	0.064	0.089	0.249	0.019	0.022	0.068	0.082
5	0.034	0.052	0.021	0.045	0.009	0.011	0	0.008
6	0.043	0.057	-	-	0.020	0.030	0.019	0.113
7	0.035	0.043	0.020	0.027	-	-	-	-
8	-	-	**0.434**	**0.434**	**0.132**	**0.141**	0.111	0.138
9	**0.299**	**0.299**	0.080	0.096	0.044	0.050	**0.570**	**0.572**
10	0.023	0.031	0.117	0.117	-	-	-	-
Mean	0.044	0.055	0.066	0.098	0.018	0.020	0.053	0.077

If the participant had not maintained a stable body posture, it was possible to verify the correctness of the XCoM parameter calculations. Figures 1a-d show how the participant changes the foot support area when leaning forward. The position of the foot taken to prevent from falling over was close to the calculated XCoM.

The usefulness of the XCoM in predicting support area in the case of balance losing during leaning out the body was confirmed.

Participant's ability to perform the exercise significantly depended on his weight and height. Normal BMI participants achieved significantly higher values of x_{GB} compared to overweight participants. Participant no. 3 has BMI = 29 and $x_{\mathrm{GB}} < 0.015$ m, whereas for the other participants BMI is less than 22 and $x_{\mathrm{GB}} > 0.04$ m.

The major aim of the paper is to find the indicator expressed in terms of the stability indicators and anthropometric parameters that would be characteristic of performed activity and approximately constant for all the participants. The participants belonged to the same age group, they failed to suffer any neurological or other disorders that could affect the studies results. It was difficult to evaluate the participant physical fitness.

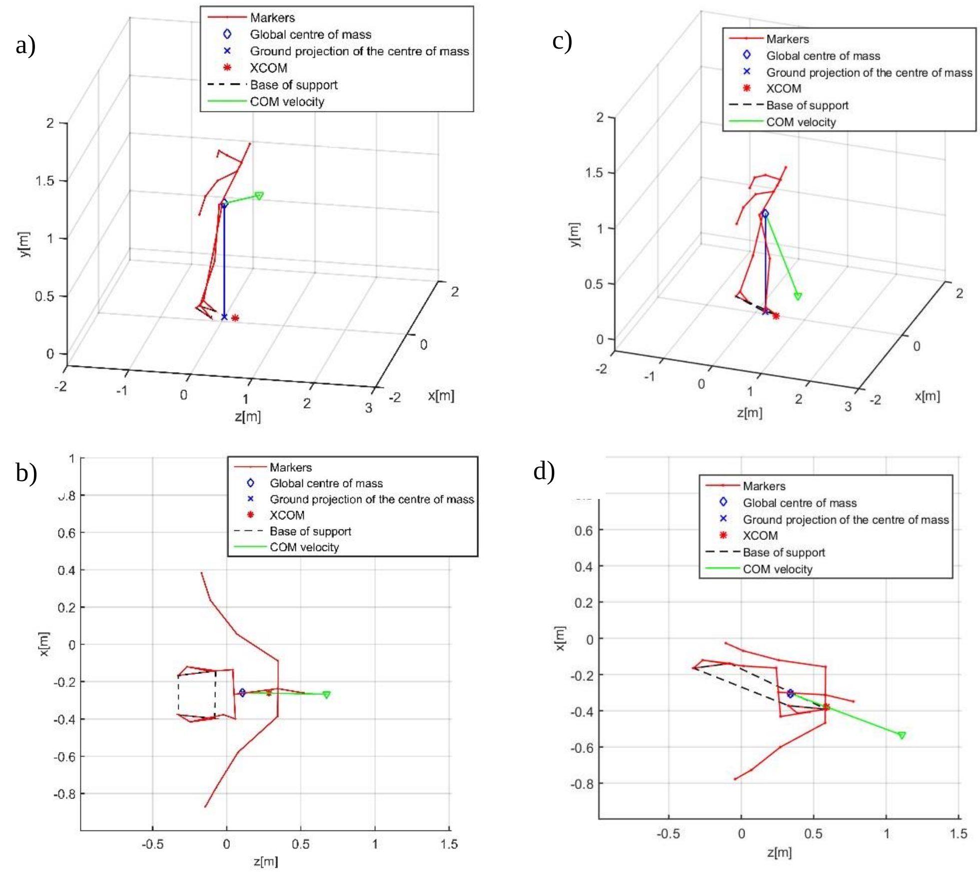

Figure 1. Loss of stability resulting in taking an additional step; a) 3D view at the time t = 4.05 s, b) top view at the time t = 4.05 s, c) 3D view at the time t = 4.35 s, d) top view at the time t = 4.35 s.

The following indicator was proposed that is expressed in terms of a stability indicator x, body mass m and body height l:

$$f(x,l,m) = x\frac{m^a}{l^b}\,. \tag{3}$$

The studies were carried out for the following stability indicators: x_{GB}, MoS i max_{MOS}. The exponents a and b from the interval $0 \le a,b \le 5$, were searched for to minimise the deviation error:

$$E = \frac{(\max(f_i) - \min(f_i))}{f_{\mathrm{AV}}}\cdot 100\%\,, \tag{4}$$

where $f_{\mathrm{AV}} = \sum_{i=1}^{n} f_i$, n - the number of participants.

Iteratively it succeeded to determine the values of a and b for the parameter.

$$x = \frac{1}{p}\sum_{j=1}^{p} \max(MoS_j) , \tag{5}$$

where p stands for the number of trials performed by a participant. The parameter is the average value of max_{MOS} in the trials, in which a participant returns to the upright posture, however, the results for the participant no. 2 were rejected. For participants no. 1, 3 and 4 the exponents are a = 2.175 and b = 4.175, and the deviation error for these participants is low and less than E = 0.1%.

For other tested indicators the deviation is greater than 15%, Let us notice that $\frac{m^{2.175}}{l^{4.175}} \approx BMI^2$. Indicator f is equal to 41.1±0.014 for each of the three participants. The value of f for participant no. 2 is significantly greater and equal to 80. The reasons can be: random incidents during the tests or some distinguished feature of participant no. 2. The higher value of f may also characterize the persons of higher ability to keep stable position. Then f also specifies the margin of the stability. Nonetheless, this thesis has to be verified in further studies. At this stage of studies, one can formulate a preliminary conclusion that the stability indicators depend on the BMI index - in this study max_{MOS} is inversely proportional to the BMI^2.

5. Conclusions

The paper is summarized in the three following points:

- The exact determination of the mass centre position has a decisive influence on the values of other parameters, e.g. x_{GB}, the position of the XCoM and the values of margins of stability MoS. An important issue is also the interpolation of the markers positions, which temporarily become not visible by cameras. Even small errors in approximation of the marker position cause significant changes in the velocity of the mass centre. These errors cause that the numerically computed acceleration of the mass centre reaches very high, non-realistic values.
- The tests allowed to verify the results of the previous studies. The results presented in the previous work [11] are characterized by too high values. In paper [11] the average distance from GCoM to BoS (denoted x_{GB} in this work) during falling backwards was 0.146 m. After conducting additional studies, in which participants try to return to the starting position, it is not possible to obtain such large values of this parameter. When leaning the body back, even a slight deflection of the GCoM outside the foot support area results in taking the auxiliary step. The margins of stability when leaning backwards is much smaller than when leaning the body forward.

The studies were performed for four participants only and one nearly static exercise. Nonetheless, the results obtained indicate the directions of further studies that will aim at verification of the relationship obtained and at determination of stability indicators for more dynamic activities. The tests have to be performed for a greater number of participants to enable statistical analysis of results. The confirmation of the dependence of the stability area size on the inverse of the square of BMI index would be a new and important observation, and the authors have not found works presenting such a relation. It seems obvious that the participant's BMI has a significant impact on the stability parameters. Incorrect body weight leads to difficulties in maintaining a stable posture when performing various movement tasks.

Acknowledgments

The research was financed from the project 0612/SBAD/3566 allocated by the Ministry of Science and Higher Education in Poland.

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