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Human Sway on a Balance Platform

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Abstract
In the body balance process control, a variety of postural strategies for balance recovery are used. Postural strategies are automatic stable muscular patterns. Such a mechanism reduces the degrees of freedom number, simplifies, speeds up the posture adjustment, and minimizes energy expenditure. They relate to the existence of some motor coordination sets and describe three mobility strategies: ankle, hip, and step strategy. The hip strategy occurs when interference is greater or the use of the ankle strategy is impossible, for example, due to the delay of the postural information cycle. From a dynamical systems point of view, a human attempting to balance upright on an unstable balance board represents the coupling of two dynamical systems, the human balance system with neuromuscular feedback supported on the balance board (an inverted pendulum). The coupling of these two dynamical systems, with time delay and nonlinearities, creates an ideal setting for the emergence of complex postural behaviour and unanticipated interactions between the individual, task, and the external dynamical system. The article presents an analysis of the pendulums concerning the issue of maintaining balance by man.

Keywords
balance, low-frequency, sway, analysis

Introduction

Consistent interoperability between skeletal, muscular, and nervous systems, creating human motion organ, is responsible for all movement activities. The nervous system is responsible for processing signals from receptors and generating the desired response by stimulation of the muscular system. It is, therefore, the role of the control system to work the muscles. In the muscle system, signals of electrochemical nature derived from the nervous system cause the contraction of the selected teams, which is in the further order on the skeleton. The muscular system creates, therefore, active motion apparatus. Skeletal muscle contraction changes distance, in the simplest case of two adjacent bones, which forces their movement while maintaining the existing restrictions. The skeletal system performs two basic functions by creating a passive motion apparatus - support for the soft parts of the body and protection for the internal organs. Motion organ in the presented form corresponds not only to the two basic motion activities, that is, locomotion and manipulation, but also to the maintenance of the human body posture. Control of standing posture is a particular element of physical activity, as a valid, stable attitude is a prerequisite for the ability to perform most human movements. (Bauby & Kuo, 2000), (Pollock et al., 2000).

In the case of a man maintaining balance in the standing position seems to be something obvious and does not require much effort. However, with the appearance of the lesion or ageing of the body, we are beginning to see how complex is the process of balance control. Changes lead to impaired control of balance which subsequently can lead to instability of the posture and extreme conditions up to the fall. Maintaining a stable posture is related mainly to the control of movement provided by the human nervous system. Equally important is, however, also the determination of the clear spatial orientation and taking into account the influence on the body of forces from different sources. The balance can be described as a postural system state, which is characterized by a vertical orientation of the body held thanks to the balance of forces and their moments acting on the body.

By dividing the human body into segments linked closely with the skeletal-joint system of the limbs and the trunk, you can create a system of linked pendulums with many degrees of freedom. In the case of a standing position, it will be largely a complicated layout of the inverted pendulums, which one can use to model the activity phenomena associated with balance and locomotion (Milko, 2012). When in a standing position, taking into account the natural motion restrictions, blocked will be movements in all the joints except the ankle joints; by a large approximation, the human body will behave as a solid rigid. It can therefore be assumed that in the case of the support of the human body in the ankle, it will be kept as the inverted pendulum. Besides, to prevent a fall, it must be held that the ankle, in addition to the rotary joint, which is the pendulum axis of rotation, must be treated as a control element. Based on the physics of the body in balance, all forces applied to the body must balance each other. This is possible thanks to the stabilization of the ankle and the forces generated by muscles (Masani et al., 2003). In conclusion, the human body in a standing position, due to the incessant alternating operation of muscle and internal organs for all time, remains moving slightly, tilting from the perfect vertical position in the sagittal and frontal planes (Frank & Earl, 1990).

The emergence of unforeseen external stimuli, which may lead to destabilization of the standing posture, requires an immediate reaction from the controlling stability system. The condition for the correct response of the mentioned system is stimulus-appropriate recognition in the shortest possible time and selecting the proper sequence to restore the balance. The limited time frame needed to restore the balance requires fast movements to compensate for the instability. To do this, a limited set of common motoric patterns is used. Increasing the counts for this set of patterns would slow the body's reactions and therefore limit the possibility of maintaining the balance for a specific case. In the elderly, a reduction in reaction speed should be expected; therefore, reducing potential rebalancing programs will increase the effectiveness of maintaining it. In old age, reducing the reaction rate can be expected and therefore reducing the potential for restoring balance will increase the effectiveness of its maintenance.

The human body standing posture control

Maintaining a proper and stable posture depends on spatial orientation, the impact of the various forces on the body, and human motor control. With limited support area, the vertical position of man is sensitive to various imbalances. Control of body posture and balance preservation are divided into two processes-the posture control and stability control of the posture. Posture control relies on giving the body a proper position. It is identified as the ability to perform motor actions when the body does not change its position concerning the ground. Posture stability control consists rather in opposition to the various distortions in the vertical position. So this is a dynamic process. These distortions can come from both the external and internal human environments. Dynamic equilibrium is, therefore, the ability to control the vertical posture when the body performs the movement in the space (Allum et al., 1998).

However, maintaining a balance between the sagittal and frontal planes will run in various ways (Fig. 1). In the frontal plane, the lower limbs and hip form a kind of frame that prevents, to some extent, loss of balance without one of the limb detachment of the ground. Otherwise, the system looks different in the sagittal plane, where a small inclination exceeding 1.5 degrees backwards and 7 degrees to the front can cause an irreversible loss of balance (Milko, 2012), (Hof et al., 2010).

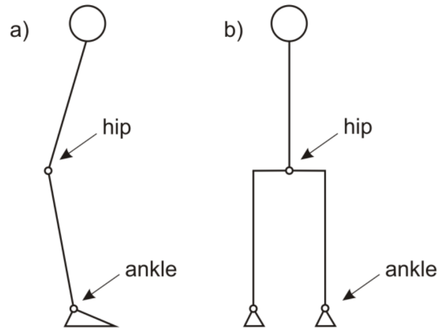

Fig. 1. Human balance: a) sagittal plane, b) frontal plane (Kot & Nawrocka, 2015)

In the body balance process control, a variety of postural strategies for balance recovery are used. Postural strategies are automatic stable muscular patterns. Such a mechanism reduces the degrees of freedom number, simplifies, and speeds up the adjustment of the posture, and minimizes energy expenditure (Frank & Earl, 1990), (Menegaldo et al., 2003), (Ringhof & Stein, 2018). They are connected with the existence of some motor coordination sets. (Horak & Nashner, 1986), (Nashner, 1997), (Nashner & McCollum, 1985) and (Winter, 1995) describes three mobility strategies (Fig. 2).

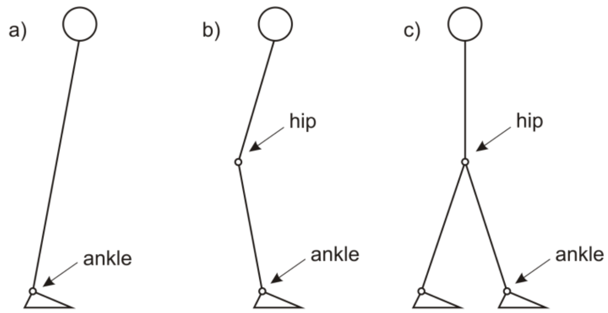

Fig. 2. Human balance strategies: a) ankle strategy, b) hip strategy, c) step strategy (Kot & Nawrocka, 2015)

The ankle strategy occurs when a person in a standing position is subjected to short-term changes in the sagittal plane during free-standing on the platform, which surface is greater than the plane of the foot's support. The ankle is the axis of the observed response. Such a strategy with little disruption occurs in the free-standing.

The hip strategy occurs when interference is greater or the use of the ankle strategy is impossible, for example, due to the delay of the postural information cycle. This occurs when a person stands on a platform smaller than the feet' surface area, where the toes and heel are not supporting the body. In the frontal plane, this strategy depends on the location and size of the application of an external acting force.

Step strategy is associated with higher deflections of the centre of gravity outside the limits of stability, i.e. in the case of a strong destabilizing stimulus. Taking a step forward increases the support surface and thus prevents the collapse in this strategy.

By analyzing the cases of the first two strategies to maintain a balance, one may notice that both, because of their physical nature, are similar to the inverted pendulums and at the reception of certain simplifying assumptions as such can be modelled.

Human balance modelling

An inverted pendulum is one of the pendulum types that has a centre of gravity above the pivot point. Such a state of affairs causes the object, apart from the undesirable lower stable equilibrium position, also has an unstable upper equilibrium position, the achievement and stabilization of which is the goal of the control algorithms used. The instability of the inverted pendulum and the fact that it is described with non-linear dynamic equations make it a frequent example analyzed in the courses on the basics of automation and control theory. There are many examples of the use of the inverted pendulum concept, both man-made and nature-created by evolution. Probably the most common example is a person whose upright posture requires constant control to maintain balance while standing, walking, and running. It has also been implemented in many technical solutions. An example may be the use of an inverted pendulum in the construction of early versions of seismographs, where its instability made it possible to register most of the disturbances. The inverted pendulum model also describes the rocket in the initial vertical take-off phase, where the propulsion generates the recoil force below the centre of gravity. Any disruption in the form of a side gust, with a wrong control algorithm, the lack or failure of the auxiliary side engines, and damage to the aerodynamic elements could lead to destabilization of the flight path and, consequently, to a crash. Currently, the inverted pendulum model is commonly used in the construction of humanoid walking robots and balancing robots that move on two wheels with a common axis of rotation. The latter influenced the development of transport platforms, the Segway Human Transporter being a popular representative for the transport of healthy people due to their commercial success. The possibility of turning in place in the case of the two-wheel balancing chassis and the ease of overcoming unevenness have determined the introduction of this type of solution in the construction of modern wheelchairs. The technical solutions used in them allow, on the one hand, to balance and ride on two wheels and, on the other hand, to overcome architectural obstacles in the balance work mode. An example of this type of solution is the iBot design, which DEKA and Toyota are currently developing.

The human body can be likened to an inverted pendulum model, and stability control is carried out in two different ways. The first one is to change the angle of the body relative to the plane of the support. This is done through the ankles. The body deviation from the vertical reaches the brain by the so-called deep feeling coming from the above joints. Signals are generated by voltage change, and the length of the muscle angles changes in joints and the distribution of pressure on the surfaces of the feet. On that basis, man can know how much his body leans out from the vertical (Kot & Nawrocka, 2015).

In further considerations presented in the following article, the case of the ankle balance strategy will be analyzed, which treats the human body as the classic inverted pendulum (Kot & Nawrocka, 2014).

It should also be noted that if one treats a man as a classic inverted pendulum, as in the case of a heavily unstable pendulum, he will seek to collapse. Therefore, it was assumed that it constantly controls its vertical position. In the case described for ankle strategy, such control is done by changing the applied torque in the ankle joint and resulting from a change in muscle strength in the foot and lower leg. Mentioned muscle strength will vary both with age and the appearance of pathological processes causing attenuation. In the article, the authors used the coefficients K and B for calculation purposes, defining the parameters of the muscles proposed by Winter (Winter, 1995), (Winter et al., 1998).

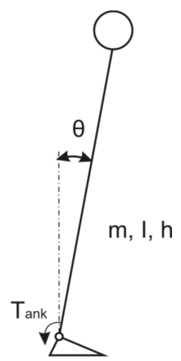

Fig. 3. Model of balance for ankle strategy

In the preliminary research model of the pendulum and the ankle torque applied to the pendulum has been constructed to assess the effect of changes in ankle stiffness, ankle viscosity, and ankle torque noise on sway size. Additionally, the study assumes that the person who is keeping the balance is standing on the ground that does not make any movement, so the system does not receive any disturbance affecting the lower limbs. The pendulum is modelled as a second-order differential equation (Kot & Nawrocka, 2014).

$$I\frac{d^2\theta}{dt^2} - T sin\theta = T_{ank}. \qquad (1)$$

The ankle torque generated by the subject was modelled as having a stiffness, viscous, and noise component.

$$-T_{ank} = K(\theta - \theta_0) + B\, {}^{d\theta}/_{dt} + w \qquad (2)$$

where:
I – inertia,
T – gravitational toppling torque per unit angle,

T_{ank} – ankle torque,
K – ankle stiffness,
B – ankle viscosity,
θ_0 – angle offset for ankle stiffness,
w – ankle torque noise.

Considering the model, ankle viscosity and stiffness allow for more accurate reproduction of behaviour in the balance, taking into account the work of antagonistic muscle pair. Applying noise to the differential equation corresponds to body sways from the vertical. These sways are caused by other muscles' work that maintains vital signs (Jeka et al. 1998). Below, the mathematical model simulation results are presented in the form of characteristics.

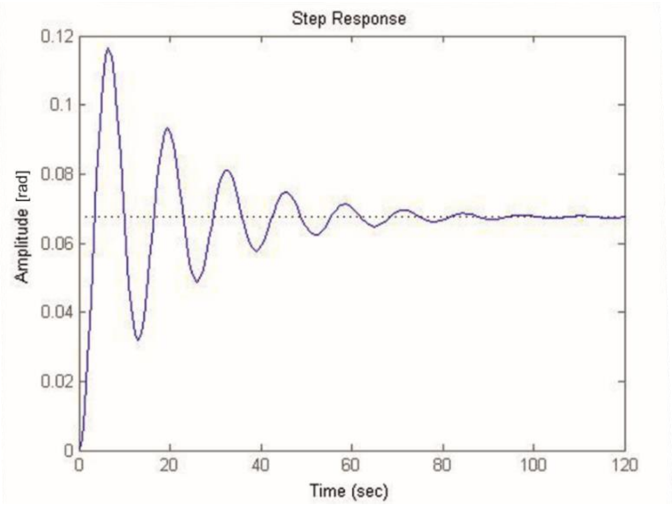

Fig. 4. Step response of inverted pendulum deflection angle for ankle strategy

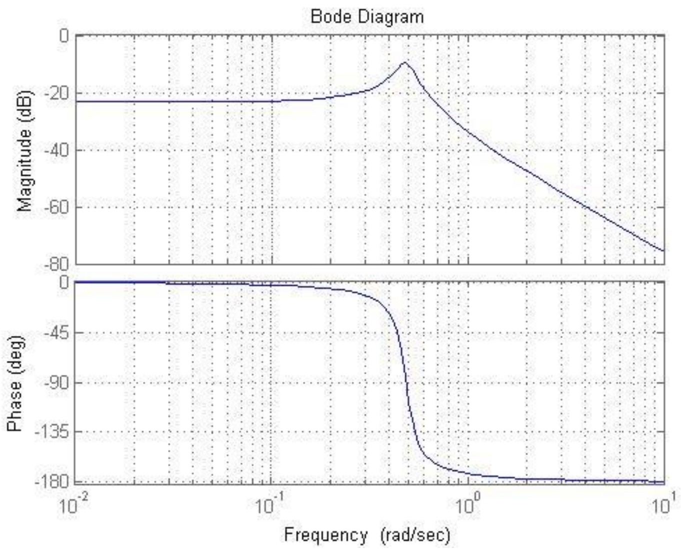

Fig. 5. Bode diagram for an inverted pendulum in the ankle strategy

The human biomechanics model in terms of a double inverted pendulum is shown in simplified form in Fig. 6. The upper segment is given by the trunk and the lower segment by the legs (excluding the feet) (Kot, 2013), (Hogan, 1985), (Runge et al., 1999). The upper inter-segment joint is the hip joint. The legs are connected to the feet through the ankle joint, with *l* giving segment length and *h* Center of Mass height. Angles are defined as trunk-leg angle θ_T and leg-space angle θ_L. (MacChietto et.al, 2009)

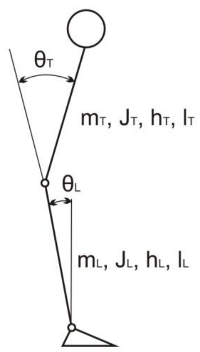

Fig. 6. Scheme of 2DOF inverted pendulum for human modelling. (Kot & Nawrocka, 2015)

For situations without external disturbances apart from gravity, the ankle torque T_{ank} required to maintain the body upright is:

$$T_{ank} = \left(J_L + J_T + m_L h_L^2 + m_T(l_L^2 + h_T^2 + 2l_L h_T)\right)\frac{d^2\theta_L}{dt^2}$$
$$+(J_T + m_T h_T^2 + m_T l_L h_T)\frac{d^2\theta_T}{dt^2}$$
$$-(m_L g h_L + m_T g l_L + m_T g h_T)\theta_L \qquad (3)$$

where $\frac{d^2\theta}{dt^2}$ represents angular acceleration, g is the gravitational acceleration, m is the mass of the segment, and J is the moment of inertia around the Center of Mass. The first two terms give the inertial torques, and the last term the gravitational torques (compare subscripts in Fig. 6)

The second term, arising from hip rotational acceleration $\frac{d^2\theta_T}{dt^2}$, represent the inter-link torques.

The hip torque T_H is given by:

$$T_H = (J_T + m_T h_T^2 + m_T l_L h_T)\frac{d^2\theta_L}{dt^2} + (J_T + m_T h_T^2)\frac{d^2\theta_T}{dt^2} - m_T g h_T \theta_L - m_T g h_T \theta_T \qquad (4)$$

where the first and second terms again represent the inertial components and the third and fourth terms the gravitational components. The first and third terms, arising from leg-space rotation, yield the inter-link torques.

In this study, we construct a double inverted pendulum model during a human quiet stance. The results of the study show that the model without active torque can be stable only if the viscoelasticity of each of the two joints is very large, which might be far from the physiological range. The model with the active torque can be stabilized if the eight parameter values of the ankle and hip joint torques are set appropriately. However, the ranges of the parameter values that can stabilize the upright posture of the model with the active torque are quite limited, meaning that the continuous and time-delay PD feedback control cannot robustly stabilize the double inverted pendulum (Laciak & Sofranko, 2014).

Testing of human balance at the balance platform

The above-mentioned approach to human balance modelling based on the ankle and hip strategies shows that it can be carried out based on the modelling principles of a single and double inverted pendulum. During modelling, one should only remember that the muscular system, in the case of a healthy person, will react antagonistically to the movement being performed.

To verify the approaches to balance modeling presented in the article, it was decided to carry out a series of measurements intended to show human behaviour while maintaining the vertical position. At the same time, such a study would allow us to determine whether, using signals with determined parameters affecting the lower limbs, such behaviours change depending on parameters or if there are no changes. The tests were carried out on the laboratory stand of a balance platform constructed in the form of a system moving in the X-Y plane, assuming that the movement of a person standing on the platform would take place in the sagittal plane (Kot & Nawrocka, 2012), (Kot & Nawrocka, 2013), (Nawrocka & Kot, 2013). Such an assumption allows us to eliminate the disturbances in motion resulting from swaying to the sides. During the research, it was decided to use excitations in the form of harmonic signals with frequencies 0.4 [Hz], 0.8 [Hz], and 1.2 [Hz]. The amplitudes of the applied signals were 100 [mm], 150 [mm] and 200 [mm]. The tests were carried out for 9 parameter combinations. To determine the character of the examined person's movement on the platform, the video system was used as a high-speed camera recording at 200 frames per second. Measuring markers were placed on the examined person in points coinciding with the axis of rotation of the joints: ankle, knee, hip, shoulder, and elbow joints and on the head. Additional markers constituting reference points have been glued on the balance platform structure. During the research, it was also decided to stick a set of markers along the spine of the examined person to determine the nature of its movement (Ahmad et al. 2019), (Ličev et al., 2011), (Robbe et al., 2014).

Examples of movement trajectories of points determined by glued markers obtained based on conducted tests are shown in Figure 7.

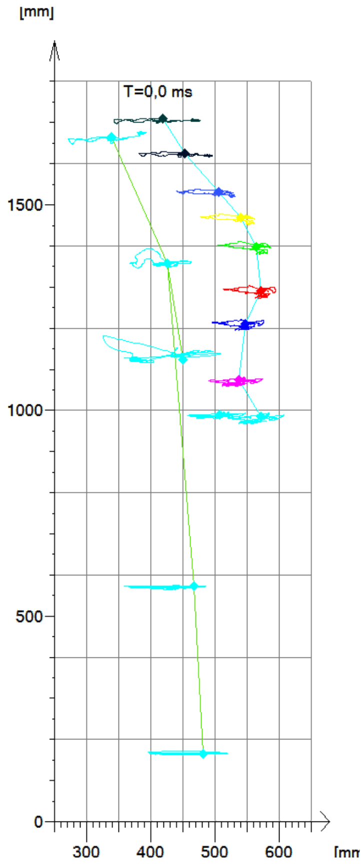

Fig. 7. Trajectories of points determined by glued markers

The following graphs show the nature of displacements (Fig. 8), velocities (Fig.9), and accelerations (Fig. 10) determined for selected points. They were recorded for the movement performed in the sagittal plane (Kot et al., 2018), (Kot & Nawrocka, 2019), (Jeka et al., 1998).

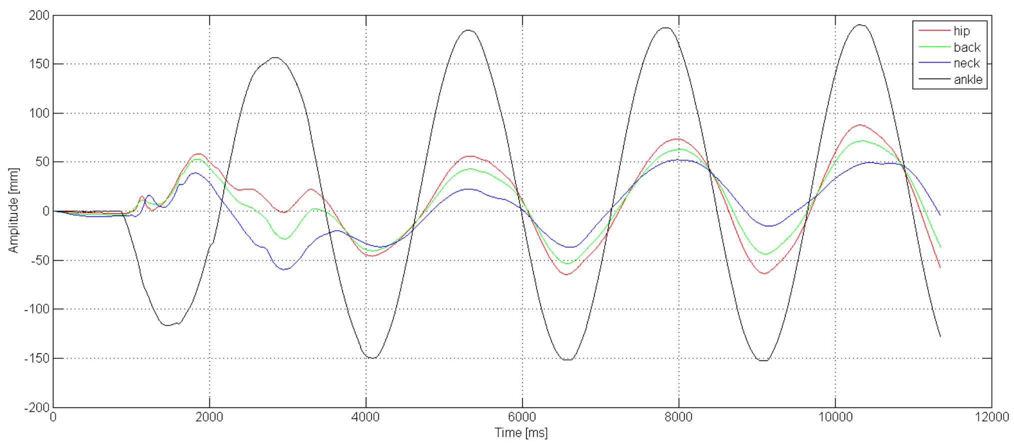

Fig. 8. Displacement of chosen points

On the basis of the observation of the results of the analysis of the trajectory of movement for individual cases of movement of the balance platform, clear differences in the nature of the behaviour of the examined person can be observed. For example, for the waveforms recorded for the platform movement frequency equal to 0.8 [Hz], clear delays in the movement for measurement points in relation to the signal forcing the movement are visible. Such a result indicates that the tested person follows the movement that the ground exerts on him, but it is impossible to precisely define this movement's nature.

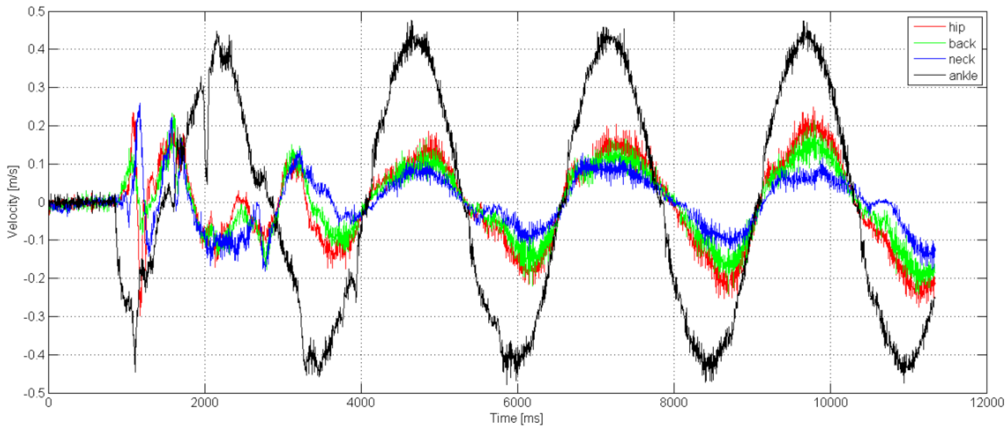

Fig. 9. Velocities of chosen points

Observation of changes in the speed value presented in the above table may lead to the conclusion that during changes in the parameters of the forcing signal, there are also changes in the method of maintaining the equilibrium. The results show that in this process, depending on the operating parameters of the balance platform, the person keeping the balance uses different strategies for maintaining the balance. In the case of the ankle strategy, when the whole body is treated as a rigid body, the velocity of individual measurement points should vary in a proportionate or similar manner. Such a tendency is visible at the lowest frequency of extortion. For the remaining cases, this proportionality is disturbed, which may suggest that the hip strategy becomes dominant in the process of maintaining the balance. In addition, an interesting phenomenon is the appearance of delays in the movement for measuring points that were located on the body at higher heights.

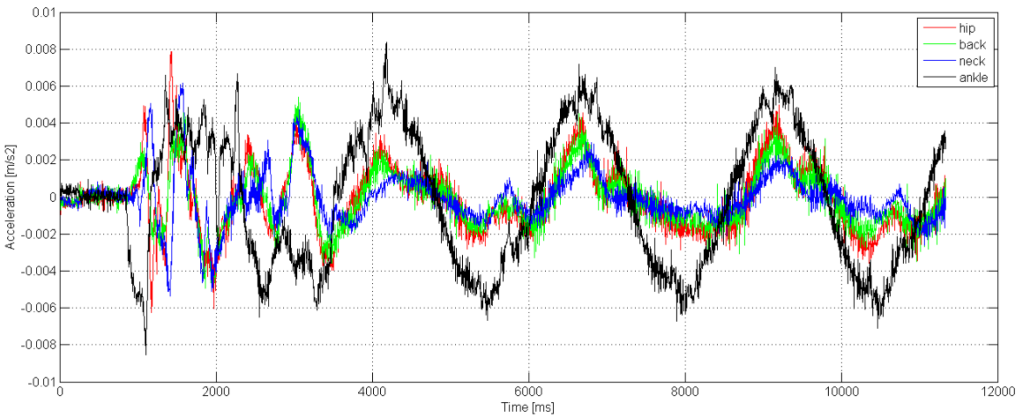

Fig. 10. Accelerations of chosen points

As mentioned earlier, both basic strategies can be modelled as inverted pendulum systems when defining the balance strategy. In the ankle strategy, it is a single inverted pendulum, while in the hip strategy, it is a double pendulum. In both cases, the degrees of the pendulum are treated as rigid bodies, and therefore for the movement around the pivot points, which are the ankle and hip joints, the acceleration of each point should be the same. The results presented above show that the accelerations are changing (Menegaldo et al., 2003), (Nashner et al., 1989). Therefore, it can be concluded that one of the steps of the pendulum can be treated as an elastic element. Existing strategies for maintaining balance, and in particular the strategy of the hip joint during modelling, can be extended by an element with elastic properties placed in the double inverted pendulum in its second stage.

As one can observe, the movement of individual points is similar to the harmonic signal being at the same time a signal affecting the lower limbs. It is also possible to reduce the amplitude of the recorded waveform with the selection of points higher and higher on the human figure. This may suggest that the balance system is working properly, keeping the head almost still.

Summary

Maintaining balance is an important skill for everyone. However, with the passage of time and the appearance of disease events, it can be seriously disturbed. The results of the research presented in the article allow stating that there is the possibility of interference in the way of maintaining balance by affecting the human lower limbs. By delving into the obtained results, it can be conclusively stated that the change in the motion parameters of the balance platform affects the change of the human reaction on the platform. Depending on the parameters, changes in the strategy of maintaining the balance appear. As part of the conducted research, the authors attempt to extend the models describing the strategies of balance with the use of elastic characteristics in models.

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