ORIGINAL ARTICLE

The segmentary mechanical work as a new instrument to postural control evaluation

O trabalho mecânico segmentar como novo instrumento de avaliação do controle postural

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ABSTRACT

Objectie: Calculate the mechanical work (W), applying the total mechanical work (Wtot) and segmental work (Wseg) as a new complementary evaluation resource of the postural control mechanisms in subjects undergoing motor and visual disturbance. **Methods:** Ten healthy adult male volunteers were selected with ages 25.6 (±2.26) years, whose height was 1.69 (± 0.25) m and body weight was 68.22 (± 0.25) kg. Kinematic data of trunk extension with eyes open and blindfolded were captured with a frequency of 200 Hz. This way the post perturbation interval has been selected and the Wseg (i.e. trunk, head, etc) and the total mechanical work (Wtot) calculated, which were obtained by means of total integral mechanical energy. **Results:** The statistical analyzing of information was done by paired-data Student's t test. There has been no significant difference ($p<0,08$) for the Wtot during the post perturbation interval. On the other hand, there has been a significant difference ($p<0.05$) in the post perturbation interval of Wseg. However, there were significant differences in interval ($p<0.05$). This difference is related to Wseg of head (Whead) and lower limbs (Wleg and Wthigh) in the post-perturbation interval with early range of [0. 60] ms and [0. 100] ms after the self-perturbation. **Conclusion:** These differences that were found in Whead between the two conditions can be associated with modulations of the vestibulo-ocular-motor system. On the other hand, the differences that were found in Wleg and Wthigh can be associated with somato-sensory adjustment mechanisms.

Keywords: Postural Balance, Mechanical Phenomena, Rehabilitation

RESUMO

Objetivo: Calcular o trabalho mecânico (W), aplicando o trabalho mecânico total (Wtot) e o trabalho segmentar (Wseg) como um novo recurso de avaliação complementar dos mecanismos de controle postural em sujeitos submetidos a perturbação motora e visual. **Método:** Dez voluntários adultos saudáveis do sexo masculino foram selecionados com idade 25,6 (± 2,26) anos, cuja altura era de 1,69 (± 0,25) m e peso corporal de 68,22 (± 0,25) kg. Os dados cinemáticos da extensão do tronco com os olhos abertos e vendados foram capturados com frequência de 200 Hz. Dessa forma, foi selecionado o intervalo pós-perturbação e o Wseg (tronco, cabeça, etc) e o trabalho mecânico total (Wtot) calculados, que foram obtidos por meio de energia mecânica total integral. **Resultados:** A análise estatística das informações foi feita pelo teste t student para dados emparelhados. Não houve diferença significativa ($p<0,08$) para a Wtot durante o intervalo pós-perturbação. Por outro lado, houve uma diferença significativa ($p<0,05$) no intervalo pós-perturbação de Wseg. Entretanto, houve diferenças significativas no intervalo ($p<0,05$). Esta diferença está relacionada com Wseg de cabeça (Wcabeça) e membros inferiores (Wperna e Wcoxa) no intervalo pós-perturbação com intervalo inicial de [0. 60] ms e [0. 100] ms após a auto-perturbação. **Conclusão:** Essas diferenças encontradas em Wcabeça entre as duas condições podem estar associadas a modulações do sistema vestibulo-ocular-motor. Por outro lado, as diferenças encontradas em Wperna e Wcoxa podem ser associadas a mecanismos de ajuste somato-sensorial.

Palavras-chave: Equilíbrio Postural, Fenômenos Mecânicos, Reabilitação

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Submitted: May 18, 2020
Accepted: June 02, 2020

How to cite
Castro PCG, Goroso DG, Coelho DB, Lopes JAF, Ayres DVM, Battistella LR. The segmentary mechanical work as a new instrument to postural control evaluation. Acta Fisiatr. 2019; 26(4):209-214.

DOI: 10.11606/issn.2317-0190.v26i4a168984

INTRODUCTION

In physics, mechanical work (*W)* results when an object moves from one point to another by the action of a force,[1] associated with changes in mechanical energy (***E***$_m$), according to the theorem of classical mechanics.[1,2] However, in biomechanics, ***W*** has helped to study human movement in activities such as cycling,[3] balance beam[4] gymnastics, pole vaulting,[5] gait, and hiking.[6-8]

The information of vector variables in the study of human posture has been a recurrent tool for many researchers in the last decades.[3-8] The use of an scalar variable such as the ***W*** or the ***Em*** of each body segment may result in an attractive analysis tool for the study of human posture.[3] This would assess the performance and efficiency of physiotherapeutic methods of rehabilitation - for example physical therapy vs conventional rehabilitation robotics in patients with spinal cord injuries or in stroke patients.

Moreover, according to Arampatzis et al.[7], there are four mathematical models used to quantify ***W***, among these the total mechanical work (W_{tot}) is better for linear correlation at low speeds (below 2.5 m/s), quantifying to small shifts in the body's center of mass (COM) caused by the body oscillations during maintenance of postural control.[9] Apart from that, Freitas & Duarte[9] showed how our body frequently is oscillating for the maintenance of postural control. This oscillation is controlled by the sensory-motor system.[10]

The visual sense has an exalted status among the sensory receptors, representing a sensory-perceptual system unique because of its ability to give information about motor control actions.[10] When visual information is unavailable, because one simply closes the eyes or is in a totally dark environment, the body's oscillations are nearly doubled,[11,12] demanding that other sensory sources be used[13] or adapted for maintaining posture.[10] Therefore through the evaluation of the oscillation of the body COM by the ***W*** it is possible to obtain information of great relevance of the postural mechanism and, with that, search for the comprehension of how the sensory nervous system is being used on a certain task.

Previous studies from Bittencourt et al.[14] and Costa et al.[15] used the estabilográficas variables, in the case of Center of pressure (COP) and electromyography to investigate the postural control through the body oscillations in situations of motor and visual disturbances, with the kinemactics variables being used only to separate the task intervals before, during and after the motor disturbance; for these studies the kinetics variables were not applied to investigate the body or segment movement. The kinetics variables such as the W_{tot} oscillation and the segmentary mechanical work W_{seg} for the comprehension of the movement of each body segment could have provided complementary information of great relevance regarding energy cost and, with that, search for comprehension of the postural control of the task of the study mentioned above.

Therefore, the interest of this study is to propose the calculation of ***W,*** applying the W_{tot} and W_{seg} as a new resource of complementary evaluation of the postural control mechanisms[3-8] in subjects undergoing motor[16,17] and visual disturbance.[15,18]

The trunk extension for upright position is a relevant task to investigate once that, not only it provides a motor disturbance, it also is a widely used task of our routine (standing up, lying down, picking up an object, etc.).

Thus, understanding the performance of the body through muscular work during motor and visual perturbation could lead to advances in the area of physical rehabilitation, specifically with the biomechanical variables analyzed which will make it possible to understand postural control when vision is not present and in situations of motor disturbance.

OBJECTIVE

This study aims to calculate the mechanical work (W), applying the total mechanical work (Wtot) and segmental work (Wseg) as a new complementary evaluation resource of the postural control mechanisms in subjects undergoing motor and visual disturbance.

METHODS

Ten healthy adult male volunteers were chosen with ages 25.6 (±2.26) years, whose height was 1.69 (± 0.25)m and body weight was 68.22 (± 0.25) kg. Before testing, the volunteer subjects were informed of the testing procedure and risks of the study, and each subject signed an informed Consent Term as approved by the Mogi das Cruzes University ethics committee (Process CEP nº 110/06 and CAAE: 0111.0.237.000-06) and by the Physical Medicine and Rehabilitation Institute of Hospital das Clinicas IMREA-HC/FMUSP from Sao Paulo (Research Protocol No. 0069/08 on 17/03/2008).

The task consisted in keeping a flexed trunk 90° from the ground; then after an initial audible command was issued, subjects made a trunk extension as fast as possible to an orthostatic position. This was done with the aim of causing self-perturbation. The same subjects remained in the orthostatic position for 8 seconds, which ended with another audible command. Eight seconds is considered an adequate time for analysis of postural motor perturbation.[9]

Each subject proceeded under two conditions: (I) initially the no-visibility (B) state, actually blindfolded (diving goggles stuffed cotton and sealed with black tape); and (II) the with-visibility (V) state, being conducted with eyes open. Five repetitions were performed on each subject for both visual conditions, of which the first two were rejected for not including the initial fitting of the experimental procedure in the data analysis; the number of repetitions is recommended so as not to cause fatigue and motor learning.[9] In addition, mean values were calculated for each variable.

For analyzing the data acquisition, corporal posture assignment markers were affixed by means of spherical, reflective, double-sided tape at 28 points on the body, whose assignment was proposed by the Dempster anthropometric model in 1955.[19] With the help of these markers it was possible to define the beginning and end of each segment, as well as to determine the COM of each segment and the body in general.

The study was carried out at the Motor Control Laboratory of the Research and Technology Center at Mogi das Cruzes University LACOM-NPT/UMC, in collaboration with the Movement Laboratory of Physical Medicine and Rehabilitation Institute at Hospital das Clinicas IMREA-HC/FMUSP. This laboratory acquires data via the Hawk digital system manufactured by Motion Analysis Corporation (Santa Rosa, California, USA). The Hawk system is composed of 8 video cameras with a capture frequency of 200 Hz, allowing images of reflective markers to be previously captured on subjects' bodies in order to create a three dimensional model of a moving body. (Figure 1).

Through reflexive markers position it is possible to determine the body segments according to the Dempster anthropometric model[19] and with that, use the system software to calculate the body and segment COM.

Equations (1a) and (1b) were used to quantify W_{tot} and W_{seg} , as proposed by Arampatzis et al.[7], which are quite efficient for calculations for speeds below 2.5 m/s.

$$W_{tot} = \int_{T_D}^{T_O} \left|\dot{E}_{Tot}\right| \cdot dt \qquad (1a)$$

$$E_{tot} = \sum_{i=1}^{N} E_i = \sum_{i=1}^{N} \left(1/2 m_i v_i^2 + 1/2 \omega_i I_i \omega_i + m_i g h_i\right) \qquad (1b)$$

Where:

Wtot: Total mechanical work; Etot: Total energy of model to 12 segments; N: Number of segments, N=12; i indicates each segment: head, trunk, and left and right arms, forearms, legs, thighs, and feet; Ei: Total energy of each segment, m: Mass of each segment; v: Velocity vector component in direction x, y, z, in relation to the COM of each segment; w: Angular velocity vector of each segment; I: Inertia tensor of each segment;[8] g: acceleration gravity; h: height of COM for each segment. The radius of gyration of the COM inertial tensor of each segment was calculated in relation to the proximal axis rotation. Associated with the total mechanical energy of each segment we have the mechanical work from each segment, which is:

$$W_i = \int_{T_D}^{T_O} \left|\dot{E}_i\right| \cdot dt \qquad (2)$$

Equation 2 represents the working muscles of each segment i = 1, N=12 (head, trunk, etc). For further information the authors recommend reading the article of Arampatzis et al.[7]

Initially, a previous analysis was made of kinematic data acquired, in order to determine the study interval, which on this research is the post perturbation interval. For thar, the Costa et al.[15] was used, and it separates the motor task in three intervals (before, during, and after post-perturbation). The pre-perturbation is an interval before any movement of trunk extension, the during-perturbation is a movement of trunk extension to an orthostatic posture, and post-perturbation is an orthostatic position after the self-perturbation in which the subject remains motionless for eight seconds.

The range of the perturbation was identified through the establishment of the movement start and end points.[15] The starting point links the beginning of the movement of extending the trunk in the z axis coordinated with the COM minimum value, which coincides with the COM's module velocity equal to zero. The ending point is associated with the COM's module velocity equal to zero, when the module of this magnitude goes from a negative to a positive value after the first one occurs. This same method was used recently by other authors to analyze this motor task[15] and demonstrated its effectiveness in the separation of respective intervals. Data were filtered by a low-pass Butterworth filter of 6th order with cutoff frequency of 10Hz.

This way, a statistical analysis of $\boldsymbol{W_{tot}}$ is necessary to compare data obtained from the ten subjects under the two conditions: V (with visibility) and B (blindfolded). These values first underwent the Kolmogorov-Smirnov[20] normality test. Taking into account that the distribution is normal, the t-Student's test has been applied for even data.[20] For these two methods, a significance level of $p < 0.05$ was applied. All calculations were performed in MatLab® programming environment, version 7.6 (2008) and the authors' own routines.

RESULTS

W_{tot} calculated

By means of equation (2) the value total energy ($\boldsymbol{E_{tot}}$) was obtained in the post perturbation interval. With $\boldsymbol{E_{tot}}$ values thus defined, $\boldsymbol{W_{tot}}$ was calculated at each interval for all subjects and the Student t-test was applied (Figure 1).

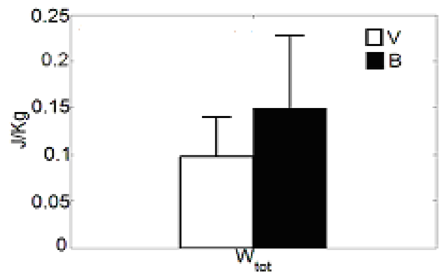

Figure 1. Mean and SD of W_{tot} (J/kg) for 10 volunteers in groups V and B during post-perturbation (c); p = 0.08

In Figure 1 is possible to observe that there has been no statistical difference (p =0.08) in the post perturbation interval, the mean value $\boldsymbol{W_{tot}}$ in the condition V is equal to 0.09 J/kg (± 0.04), and 0.14 J/kg (± 0.08) in condition B.

This result suggests that the absence of visibility did not influence the maintenance of postural control after subjects have undergone motor disturbance. Such result differs from the literature, because vision has a significant influence in postural control, because modulates the orientation of body segments (trunk, limbs and head);[10] this modulation is obtained by the synchronized action of muscles, called muscle synergy.[10, 21]

Therefore, this study suggests that $\boldsymbol{W_{tot}}$ is not an appropriate method to quantify the body oscillation during posture maintenance. To answer this paradox researchers have directed the investigation to the calculation of $\boldsymbol{W_{seg}}$ (trunk, head, upper and lower limbs) intending to comprehend the postural mechanisms adopted by the volunteers, and understanding by these mechanisms supported by literature if $\boldsymbol{W_{seg}}$ can be considered a relevant method for the quantification of postural control.

We calculated the muscular work of the body segment during the interval of post-perturbation for both visual conditions and a sequencing method was applied to compute the first milliseconds of post-perturbation. Thus, it was chosen the intervals [0, 80] ms and [0, 100] ms post-perturbation representing different periods of muscular responses (fast and slow, respectively) to the limbs muscles, independent of reflex mechanisms.[22]

Muscular work (*W*) of the body segment during the post-perturbation interval

In order to understand why only $\boldsymbol{W_{tot}}$ presents differences in post-perturbation interval we analyzed $\boldsymbol{W_i}$ for each body segment. $\boldsymbol{E_i}$ is calculated for each segment according to the terms of the summation of equation 1b, and then the $\boldsymbol{W_i}$, respectively.

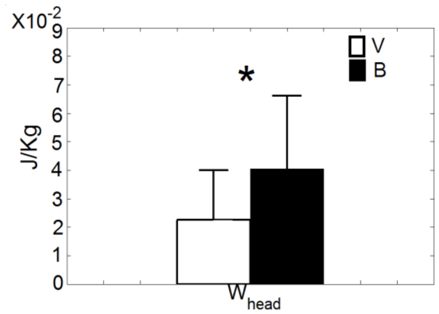

Figure 2. Mean and standard deviation Whead (J / kg) for both visual conditions during post-perturbation interval; (*) Statistical significance p = 0.03

Figure 2 shows the results of the average of the $\boldsymbol{W_{head}}$, obtained in the head segment of 10 subjects for post-perturbation interval under V and B conditions. We demonstrate that there is a significant variation p<0.05 (p=0.03), to which value is 0.02 J/ Kg (± 0.02) for V condition and 0.04 J/Kg (± 0.02) for B condition, verifying that the subjects have a motor adjustment (Figure 2).

As shown in Figure 2, the $\boldsymbol{W_{head}}$ in condition B is about twice that in condition V. This is due to a positive variation of the mechanical energy of the segment. This could be attributed to more variation in the kinetic energy of rotation in relation to the variation of potential energy, since the variation in height is almost equal in both conditions because it is the same sample of experimental subjects.

Consequently, we can say that the head oscillates more in condition B, not necessarily double in the condition V, and this increased rotational energy contributes to increased mechanical work of the muscles supporting the head in the upright position. The $\boldsymbol{W_{seg}}$ calculated for trunk and upper limbs have not shown significant statistical differences (p>0.05, p=0.10). However, significant differences were found (p <0.05) in the muscular work of the lower limbs. However, the analysis presented in this article was directed to the intervals [0, 80] ms and [0, 100] ms of post-perturbation, which is described next.

Muscular work in lower limbs at post-perturbation intervals of [0, 80] ms and [0, 100] ms

The muscle groups of the lower limbs for maintaining postural control in individuals with intact neurological systems are activated within milliseconds so that the muscles are forced to act together (muscle synergies).[10,21] The response to mechanical or electric proprioceptive stimulation is on the order of 80 ms for the quick response, and 100 ms for the slow response.[21] Therefore these intervals were chosen in order to examine quantitative differences after the occurrence of self-disturbance when comparing the two visual conditions.

It can be seen in Figure 3 that the mechanical work done by the muscular forces of the right and left thigh to maintain posture is approximately two times higher in condition B than in condition V. This result leads us to the fact that in condition B, subjects needed to use more force to maintain the dynamic balance to achieve upright posture because of the lack of visibility. This often leads to feelings of insecurity brought on by body imbalance due to lack of clear positioning feedback, where targeted movement comes only from proprioception.

Moreover, this observed difference between the two visual conditions during the interval of [0, 100] ms after the onset of self-perturbation may be related to the type of muscle fibres recruited in the case of motor responses without afferent visual stimulus , such as in condition B. The action of the leg muscles is shown in Figure 3; in this case the W is mainly associated with involvement of the tibialis anterior (TA) in the interval [0.80] ms.

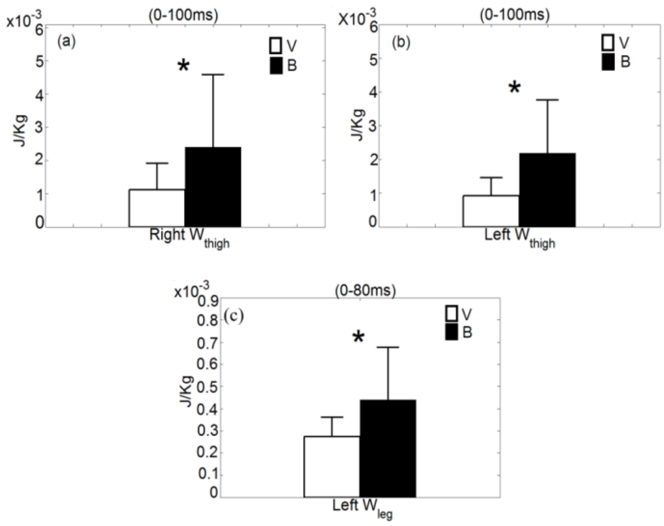

Figure 3. Mean and standard deviation for both visual conditions during post-perturbation interval . (a) Right Wthigh, (b) Left Wthig [0-100] ms, (c) left Wleg [0-80] ms, statistical significance p < 0.05

Due to the result shown in Figure 3 it is assumed that in the absence of visibility, the TA muscle played a key role in maintaining posture when the establishment of the upright posture occurs after posterior inclination of the body at the height of the downturn, which concurs with the results obtained in studies by Latash et al.[21] and Fujiwara et al.[23]

Prior to calculating the W, we obtained the curves for mechanical power through which one can verify an activation sequence that repeats itself: the foot muscle action associated with the TA muscle action of the legs associated with the gastronecmius lateral (GL), the semitendinosus (ST), and the muscular action of the trunk associated with iliocostalis (IC). Thus, this pattern is synergistic with the fact that, by extending the hip muscle, concentric GL does work to produce enough joint torque to reduce the angle of the talus/tibia-fibula (the ankle was in dorsiflexion of the fixed foot position due to the low knee flexion), and the ST muscle does concentric work to produce joint torque sufficient to reduce the angle of the iliac-femoral (which was flexed on the femur fixed) at the beginning of the drive when the COM moves in the direction z. These temporal sequences of peak strength in the muscle contractions justify their actions as antagonists of hip extension (in the initiation of movement) and trunk (in continuity).

DISCUSSION

Initially, according to Figure 2 we observe that the $\boldsymbol{W_{tot}}$ was not statistically significant (p=0.08) in the post perturbation interval in condition B. However this study is contradictory to the literature, because according to Diener et al.[24] with the absence of vision the body oscillations almost double, which would increase the $\boldsymbol{W_{tot}}$.

Although this variable was not significantly different, this leads to the question: Is there a segment or are there different segments of the body that present a significant difference (p <0.05) between the two visual conditions after undergoing motor perturbation? The analysis stage provided an answer to this question. It has been discovered that $\boldsymbol{W_i}$ (i.e: head and lower limbs) in the after disturbance interval shows significant differences (p <0.05) for the head (Figure 2) and lower limbs (Figure 3).

In the first case, it was possibly due to the strong influence of the vestibular system to maintain postural control. According to Massion & Woolacott,[25] maintaining control of posture is guaranteed by the vestibular system influencing the postural responses that are activated by head orientation.

No differences were found among the first milliseconds of post-disturbance (ranges of latency) to the head segment, because the nervous system gives greater importance to the somatosensory information in postural control (on a non-pathological case) than for the vestibular system-mostly because the somatosensory system has a fairly quick latency response (less than 60 ms), which indicates that the contribution of the vestibular system is less than that of the somatosensory in maintaining postural control for quick responses to perturbations.[26]

The $\boldsymbol{W_{thigh}}$ (Figure 3) readings observed in the range between 0 and 100 ms were statistically different between the right thigh (p = 0.03) (Figure 3a) and left (p = 0.03) (Figure 3b), with higher values of $\boldsymbol{W_{thigh}}$ for the condition B. These statistical differences were found only in the first milliseconds (intervals of latency) due to quick action of the thigh muscles in an attempt to control body sway and restore postural control.

In agreement, Massion & Woollacott[25] and Dietz et al.[26] reported that the latency of muscular response to the somatosensory system are 80 to 100 ms in cases of motor self-perturbation, and the nervous system depends mainly on the somatosensory system to control body sway when the imbalance has been caused by a rapid shift.

For the $\boldsymbol{W_{leg}}$ interval [0, 80] ms post-perturbation there was a statistical difference (p = 0.05), more $\boldsymbol{W_{leg}}$ to the condition B, suggesting that the lack of visibility has contributed to an increase in $\boldsymbol{W}$. This result suggests that the subjects had a more rapid response to maintain postural control by the muscles of the leg (lower latency) than the thigh (Figure 3).

This response with a shorter time lag can be explained by the studies of Nashner[27,29] reporting that activation of the *gastrocnemius* occurs between 20 and 30ms before the thigh muscles (in this case the ischiotibials); this activation occurs when there is a shift from the forward body that produces a torque of plantar flexion causing a slowdown and reversal of the direction of displacement.

In the trunk, there were no statistically significant differences in the range of post-perturbation and withdrawal latency, suggesting that the lower limbs were extremely important to restore control of posture after a motor perturbation.

As observed by the discussion in the preceding paragraphs, there were statistically significant differences in $\boldsymbol{W_{head}}$, $\boldsymbol{W_{thigh}}$, and $\boldsymbol{W_{leg}}$ during post-perturbation intervals.

In a recent study, Costa et al.[15] obtained similar results using kinetic variables to investigate the same motor task (trunk extension to upright posture). The authors found that the lack of visibility causes a body imbalance mostly in the range of post-disturbance being higher for the volunteers in condition B, although this study has not been able to answer, through the kinetic variables, what was the response of each body segment during the postural unbalance, being this the great differential of the present study. In study proposed by Bittencour et al.[14] besides the kinetic variables, electromyography has been used, however it did not quantify the efficiency of body segment movements, in this case the $\boldsymbol{W_{seg}}$ could be a n excellent complementary resource of investigation.

The investigation of body segment movements as suggested by the present study obtaining ***W***, mainly de differences founded on the lower limbs may bring relevant information. For instance, studies using kinectic variables with hemiplegic patients, being able to provide information on how the lower limbs behave when bearing a higher weight load on the healthy limbs during maintenance of postural control.[30]

The higher values of ***W*** calculated for the post-perturbation interval in the subjects in condition B were possibly caused by greater oscillation of the COM—this consequently led to more muscular work of the lower limbs and head.[19] Paulus et al.[11,12] reports that the body sway almost doubles when this visual information is eliminated. In agreement, Costa et al.[15] reported in their study an increase in body sway in subjects with B after the motor perturbation. Therefore, the findings reported in this study are to complement the biomechanical analysis of upright posture.

CONCLUSIONS

The results of this study indicate the method of calculating the ***W*** to analyze the effects of a motor disturbance. Regarding the differences found for $\boldsymbol{W_{head}}$, $\boldsymbol{W_{thigh}}$, $\boldsymbol{W_{leg}}$ for conditions with V and B post-perturbation it was concluded that the absence of visibility contributed significantly to the increased ***W***, occasioned by the somatosensory system, which suggests that $\boldsymbol{W_{seg}}$ (mainly on the lower limbs) can be a complementary tool to the investigation of quick motor responses form the muscles synergy.

But these differences were mainly found in the lower limbs during the first milliseconds after the motor disorder, demonstrating that they presented more of these variations because quick movements are made in response to disturbance to try to restore postural control.

As for the differences found in the head, they were caused by the vestibular system and were not found in the first moments after the motor disturbance, due to the preference of the nervous system in controlling the maintenance of posture by the somatosensory system in the first milliseconds after a motor disturbance.

The physical-mathematical method used in this study was effective for the quantification of postural control in healthy individuals and may also be a nice feature to evaluate the gain in amplitude of motion and motor control of individuals with neurological disorders treated with conventional physiotherapy, hydrotherapy, hippotherapy, or using robotic orthesis.

To finish, the relevance of the approach of the present study is to provide a more detailed comprehension of oscillatory movement of each body segment during synergy actions, leading to a great advantage in kinetic (which investigate only the COP oscillation) and in the electromyographic analysis, which provide only the muscle contraction information and not how was the movement of this segments.

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