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SCIENCE DIRECT
Gait & Posture 23 (2006) 17–21
GAIT & POSTURE
www.elsevier.com/locate/gaitpost

Postural strategy to keep balance on the seesaw

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Received 8 October 2003; received in revised form 20 October 2004; accepted 8 November 2004

Abstract

This work investigates the kinematic and electromyography (EMG) strategy used by the central nervous system (CNS) to keep equilibrium during anterior–posterior balance on seesaws with different degrees of instability. The movement of hip, knee, and ankle were reconstructed using a 3D motion-analysis system and the EMG activities of selected ankle, knee, and hip muscles were recorded. Balance was kept mainly at the ankle joint. The EMG patterns of the gastrocnemius and anterior tibialis alternated between agonist and antagonist bursts. The agonist burst started before the end of the lengthening phase and was prolonged until the end of the shortening phase. The EMG activities of the muscles crossing the knee and hip joints were characterized by a pattern of generalized co-activation. The movements at these two joints were very small, suggesting a neural or biomechanical constraint underlying the operations of the equilibrium control. Our results also indicate that the strategy to keep balance on the seesaw is qualitatively the same for the different levels of mechanical demands in terms of the seesaw's instability.

Keywords: Balance; Seesaw; Posture; Strategy

1. Introduction

An experimental approach to study how the central nervous system (CNS) reacts to maintain balance in response to external forces involves disrupting the equilibrium of an individual standing on a force platform and recording the resulting muscle responses [1,2,3,4,5]. Such studies have revealed muscle activation patterns known as muscle synergies [2] or movement strategies [4]. Many types of postural strategies have been well-characterized [6,7,8]. The CNS chooses the best strategy to maintain equilibrium according to the mechanical demand of the task. The latter varies with the type of platform, such as standing on a rigid floor [9], on a movable base of a support [10], or on a seesaw [1,11].

During quiet stance on a flat, stable platform, individuals sway slightly and the body oscillates around the ankle–joint axis, similar to an inverted pendulum [12]. On the other hand, when standing on a seesaw, humans project the center of gravity onto the seesaw's point of contact with the floor [11,13]. Studies using seesaws [11] have shown marked modulation of the electromyography (EMG) activities characterized by increased activation of the soleus during the muscle-shortening phase, but not during the muscle-lengthening phase. However, the authors did not analyze the kinematic and EMG patterns of the agonist and antagonist muscles crossing the focal (ankle joint) and non-focal joints (i.e., knee and hip).

We still do not know when and how the agonist and antagonist activities change to project the center of gravity onto the seesaw's point of contact with the floor. Nor do we

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doi:10.1016/j.gaitpost.2004.11.020

know the effect that different degrees of seesaw instability have on the modulation of these EMG activities.

The aim of this study is to describe the kinematic and EMG activities of the focal and non-focal joints necessary to keep the center of gravity on the seesaw's point of contact with the floor during anterior–posterior balance. We describe when and how these activities change as the muscles shift from the lengthening to the shortening phase, and how these changes are affected by different degrees of seesaw instability. We also describe the kinematic movements at these three joints during balance.

The effect of training on the externally imposed movements on the seesaw platforms was studied in a variety of patients [14,15]. However, there is no study about the use of free balance on the seesaw, even though it is a common tool used in Physical Therapy practice. The free balance is also an inexpensive and readily available tool and this study is necessary to support the decision for its use as an appropriate treatment.

2. Material and methods

Six individuals (three male and three female, average age 24.5 years) were studied after they had signed an institutional (UNICAMP) term of informed consent. The individuals balanced on nine moveable seesaws (30 cm wide × 45 cm long) that varied in radius (30, 60, and 120 cm each) and height (7, 12, and 17 cm). The seesaws were based on their radius and height to provide an index of difficulty (ID) for balancing (Table 1) (Fig. 1).

2.1. Kinematic data

The X, Y and Z coordinates of the LED marks were recorded using a 3D-motion-analysis system (OPTOTRAK 3020). The LED marks were attached on the left side of the shoulder (lateral aspect of the humerus), hip (between the greater trochanter and superior iliac crest), knee (lateral condyle), ankle (external malleolus), foot (head of the fifth metatarsal), and on the seesaw. The light emitting diodes (LED) coordinates were recorded at 100 Hz and used to calculate the ankle, knee, and hip angular displacements.

2.2. EMG activities

The activities of the gastrocnemius medialis (GM), tibialis anterior (TA), biceps femoris (BF), rectus femoris (RF), erector spinae (ES) at the L4 level and the rectus abdominis (RA) were recorded using bipolar surface EMG electrodes (DeLSys). All data were band pass filtered (45–450 Hz), amplified (2000×) and digitized at 1000 Hz. The EMG signals were rectified and smoothed using a second order Butterworth filter with 10 Hz cut-off frequency.

Table 1
The radius and height of all nine seesaws

Index of difficult	1	2	3	4	5	6	7	8	9
Radius (cm)	120	120	120	60	60	60	30	30	30
Height (cm)	7	12	17	7	12	17	7	12	17

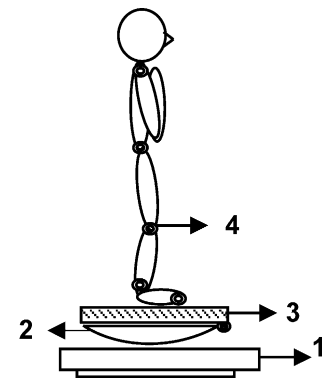

Fig. 1. Illustration of the experimental setup: (1) fixed force platform; (2) seesaw; (3) block of polystyrene; (4) LED marks.

2.3. Procedure

The seesaw was centered on a force platform and the location was marked and constantly checked to avoid seesaw translation. The investigator helped the individual to stand on a seesaw and ensured that his/her feet were proportionately arranged on the center of the seesaw. Initially, the individual was blindfolded with a mask and his/her ankle was kept in a neutral position, with the top of the seesaw parallel to the floor. From this initial position, the individual could start balancing with no external support or constraint. Also, during the balance, the individual held each shoulder with the opposite hand, keeping the upper limbs crossed and in contact with the chest. Plantar flexion (PF) and dorsal flexion (DF) are the major movements observed at the ankle joint and, because of that, we chose to analyze the data just at the anterior–posterior displacement.

Two trials of 10 s each were recorded for each seesaw, proceeding from the easiest (ID = 1) to the most difficult (ID = 9). This sequence was used to guarantee the safety of the subject who might fall off the most unstable seesaw. After two trials of balancing without getting off, the individual was evaluated on the subsequent seesaw. No instruction was given as to how to keep balance and each individual was free to choose any strategy.

2.4. Data quantification

The Matlab routine was used to calculate the maximum plantar and dorsal ankle flexion and the corresponding angular displacement of the hip and knee joints during this time. The activities of the six muscles cited above were integrated during 50 ms, just before and 50 ms after the maximum dorsal and plantar flexion time. The EMG values were normalized to the values obtained during stationary standing.

2.5. Statistical analysis

All EMG and kinematic variables were studied using ANOVA with two factors per individual; the index of difficulty (ID from 1 to 9) and movement direction (dorsal versus plantar flexion) for all kinematic and EMG variables analyzed. The interaction between the two factors was further explored using pair comparison. The EMG variables were also compared when the individual was on the seesaw and on the rigid platform, using *t*-test. Alpha was set at 0.5 for all tests.

3. Results

Fig. 2 depicts the muscle activation patterns of the gastrocnemius medialis, tibialis anterior and the ankle–joint displacement during the balance of a representative individual on seesaw ID = 7. The individual kept balance by alternating the activation of the tibialis anterior and the gastrocnemius medialis muscles. The activation of the gastrocnemius started before the ankle moved from dorsal to plantar flexion (first vertical broken line) and remained until the ankle shifted again into dorsal flexion (second vertical broken line). The activation of the tibialis anterior started before the ankle shifted into dorsal flexion (second broken line), and remained active until the ankle shifted again into plantar flexion (third vertical broken line). This EMG

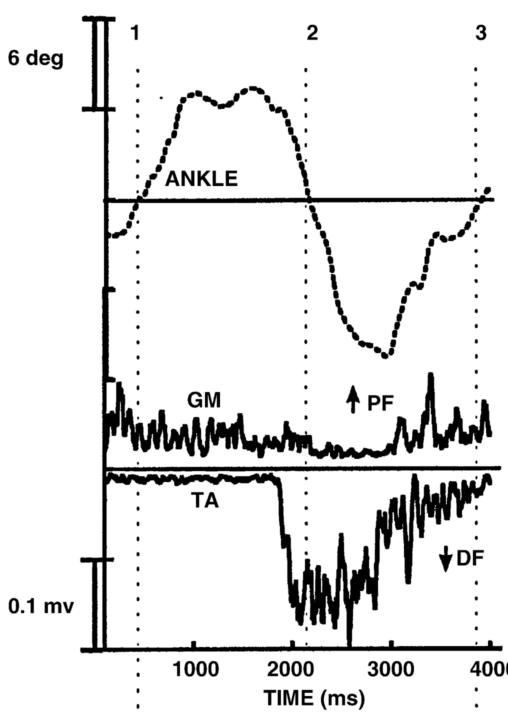

Fig. 2. Balance on a seesaw with an index of difficulty of 7. Positive values are for plantar flexion (PF) and negative for dorsal flexion (DF). The broken line shows the angular displacement of the ankle and the solid line shows the activities of the gastrocnemius medialis (GM) positive, and tibialis anterior (TA) negative values.

strategy used to keep balance on the seesaw was observed for all individuals analyzed on all nine seesaws (see Fig. 3).

3.1. The effect of movement direction and index of difficulty on EMG and kinematic variables

The main effect of the ID and movement direction (dorsal flexion versus plantar flexion) on EMG and kinematic variables analyzed using two-way ANOVA is shown in Table 2.

When the ankle was at maximum dorsal flexion, the TA activity was higher compared to the time the ankle was at maximum plantar flexion. The opposite was true for the GM and BF. On the other hand, the RF, ES, and RA activities did not vary significantly when the ankle was at maximum dorsal flexion or plantar flexion.

The activities of TA and RA were modulated with the index of difficulty and this modulation was close enough to be considered significant for the ES. However, the seesaw's index of difficulty did not significantly affect the amount of EMG activities of GM, BF, and RF, when the ankle was either in dorsal flexion or in plantar flexion.

The only significant interaction between the movement direction and index of difficulty was observed for TA. The pair comparison analysis revealed that, for stable seesaws (from ID = 1–4), the amount of TA activity was similar for both dorsal and plantar flexion ($F > 1.85$, $p > 0.10$) and, for unstable seesaws (ID = 5–9), the amount of TA activity increased during dorsal flexion ($F > 13.47$, $p < 0.05$).

The seesaw's index of difficulty significantly affected the movement of the ankle, but not the movement of the knee and hip. The hip and knee movements were statistically similar during plantar flexion and dorsal flexion.

4. Discussion

4.1. Strategy used to keep balance on the seesaw

Even on the more unstable seesaws, all individuals were able to keep balance without falling during a period of 10 s. Mainly, they did so by moving the ankle joint, whereas the hip and knee movements were at the range where the individuals stood still on a rigid platform. If one considers just the major joint involved in the correction of the imbalance, the kinematic strategy on the seesaw could be compared with the so-called "ankle strategy", used to keep balance on the translational platform, with a large base of support for the body [6]. However, the direction of the ankle movements is different when comparing the seesaw and the translational platform [6].

As the seesaw rotates forward, the foot rotates into plantar flexion. This movement is achieved due to strong eccentric contraction of the gastrocnemius, which initiates at the end of the dorsal flexion. As the ankle reverses direction from dorsal flexion into plantar flexion, the activation of the

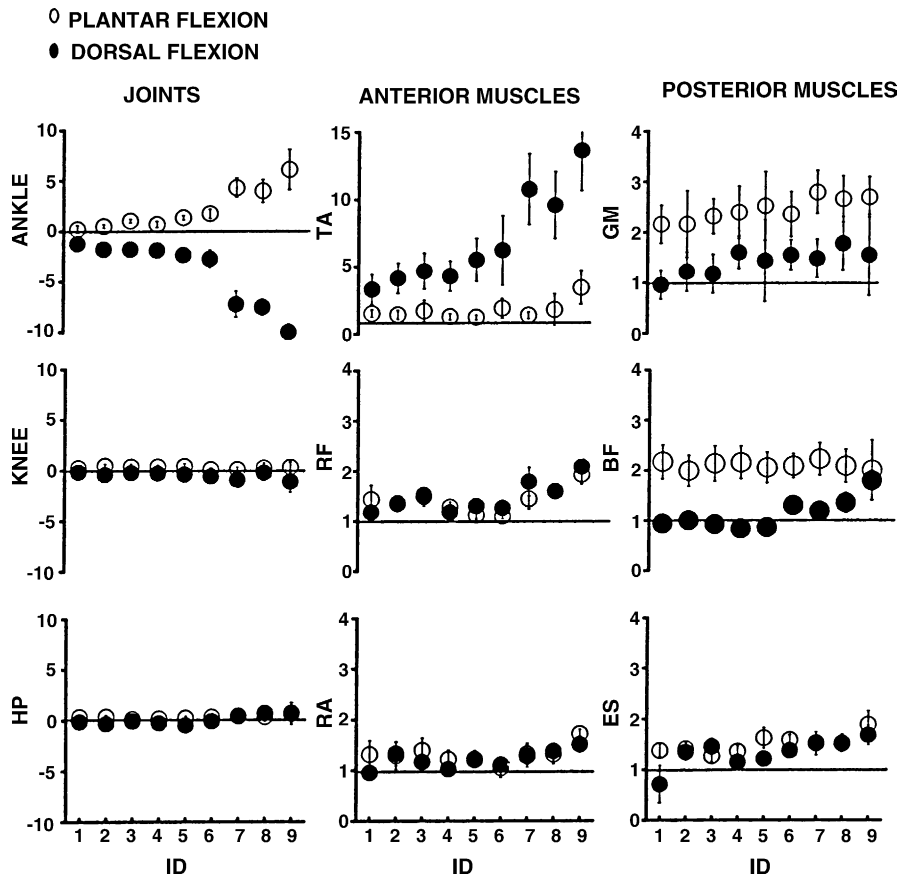

Fig. 3. The displacement of the ankle, knee, and hip angular excursions, and the integrated EMG activities of the tibialis anterior (TA), gastrocnemius medialis (GM), rectus femoris (RF), biceps femoris (BF), rectus abdominis (RA), and erector spinae (ES) during maximum plantar flexion (open circles) and dorsal flexion (closed circles). Data represent mean values obtained from six individuals. The muscle activities were normalized and are unitless. The vertical lines represent the standard error.

gastrocnemius changes to a concentric mode of contraction. Around the maximum plantar flexion, the gastrocnemius activities are still high and the activities of the TA are reduced. Then, the ankle movement is reversed once again into dorsal flexion because of the strong eccentric activation of the TA. This pattern of alternation between the activation of the anterior and posterior muscle is continuous during the balance.

Table 2
ANOVA test for the kinematics, kinetic, and electromyography variables

	Direction		Index of difficult		Direction × index of difficult	
	F	*p*	*F*	*p*	*F*	*p*
TA	10.35	0.02*	4.29	0.00*	5.36	0.00*
GM	6.68	0.05*	0.88	0.53	0.27	0.97
RF	1.05	0.35	2.23	0.45	1.58	0.16
BF	50.09	0.00*	0.31	0.95	1.56	0.17
RA	1.77	0.24	2.27	0.05*	0.65	0.73
ES	3.66	0.11	1.91	0.08	0.82	0.58
Ankle	40.05	0.00*	28.85	0.00*	5.40	0.00*
Knee	6.03	0.06	0.32	0.85	0.78	0.67
Hip	4.32	0.09	2.06	0.06	0.56	0.89

For balance on a seesaw, Ivanenko et al. [11] reported marked modulation of the EMG activities, characterized by increased activation of the soleus during the muscle-shortening phase, but not during the muscle-lengthening phase. Our results differ from the observations of Ivanenko et al. [11] in three ways. First, the agonist burst started before the end of the lengthening phase (eccentric mode) and was prolonged until the end of the shortening phase (concentric mode). The anticipation of the agonist muscle activation in relation to the time when the ankle shifted direction allows the CNS to react and prevent a large ankle movement that could cause the loss of balance. The muscle generates larger muscle torque when activated during the lengthening phase (eccentric contraction) than during the shortening phase (concentric contraction) [16]. Thus, this anticipation of the agonist muscle could take advantage of the lengthening contraction to better react to the postural disturbance. Second, this EMG strategy is preserved over different ranges of seesaw instability in terms of agonist and antagonist EMG patterns. Third, by showing that the kinematics and EMG activities of the muscles crossing the hip and the knee joints operate to create a rigid body that can oscillate mainly at the ankle joint. This rigid body can be explained by the fact that the activities of the muscles crossing the knee and hip joints (RF, RA, and ES) were similar when the body oscillated into dorsal or plantar flexion, creating a pattern of co-activation between the anterior and posterior muscles, which could increase stiffness of the joints, favoring the stability of the body during the oscillation on a seesaw.

4.2. Practical implication

The use of a seesaw is a common procedure adopted by Physical Therapists for patients with a variety of movement dysfunctions. However, there is no clear explanation about the strategy used by the CNS to keep balance on a seesaw, which is essential if one wants to test the real effect of the seesaw on the recovery of movement control. Our results indicate that the strategy to keep balance on the seesaw is qualitatively the same for different levels of mechanical demands in terms of the seesaw's instability. So, the Physical Therapist can graduate the index of the seesaw's difficulty according to the physical condition of the patient. The impact of repetitive training of this strategy on the motor function of daily activities is however, not known.

4.3. Limitations of the study

The greatest difficulty found in this study was related to the control of the frequency and amplitude of seesaw sway. The fact that the individual was free to sway in his or her own way allows the task to be more "realistic". However, this flexibility challenges the quantitative control of the sway (i.e., frequency, amplitude, and velocity). Also, the degree of seesaw instability was determined by the combination of the radius and the height of each seesaw, and did not necessarily increase by a constant magnitude from one seesaw to another.

4.4. General conclusions

During balance on a seesaw the kinematics and EMG activities of the muscles crossing the hip and the knee joints operate to create a rigid body that can oscillate mainly at the ankle joint. The EMG patterns of the GM and TA alternated between agonist and antagonist bursts, with the agonist burst initiating at the end of the lengthening phase. These patterns of EMG activities were not affected by the degree of stability of the seesaw. With the increment of the seesaw's degree of instability, the CNS simply has to scale this pattern to generate the appropriate level of correction.

Acknowledgements

Authors thank FAPESP – FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO for financial support – (Grant no. 98/06866-8).

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