Bilateral Simultaneous Measurements of Standing Ground Reaction Forces in Hemiparetics, Below-Knee Amputees, and Healthy Adults

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Abstract

In this study standing balance activity was investigated in hemiparetics, below-knee amputees, and healthy control subjects by measuring the foot-ground reactive forces in each limb separately and simultaneously. Forces in the anteroposterior and mediolateral directions were monitored by means of two force platforms. Values obtained from both legs were compared and their ratios were calculated. In the hemiparetics and amputees, the anteroposterior forces were significantly larger (p 0.05) in the sound limbs as compared to the affected limbs, both with the eyes open and closed. The anteroposterior/mediolateral force ratio in amputees was significantly smaller (p 0.01) in the amputated limb, both with the eyes open and closed. This ratio was also found significantly different (p 0.05) when comparing the amputees group and the healthy group: in the amputated limb it was smaller than in the healthy group and in the sound limb it was larger. The activity in the anteroposterior direction of the sound limb in amputees, and to a lesser extent in hemiparetics and healthy, assumes the main role in regulating the standing balance. Therefore, amputees and hemiparetics should be trained in equilibrium exercises to improve the ability of the affected limb hence reduce load over the sound limb in the process of maintaining standing posture.

Key words: standing balance, hemiplegics, amputees.

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The human upright position is an unstable situation which requires the presence of active mechanisms and continuous feedback in order to maintain balance [8, 11, 12]. In fact, signals from the somatosensory, vestibular, and visual systems integrated within the locomotor and central nervous systems engender motor responses involved in a constant regulation of balance [3, 16]. The ability to maintain the erect posture and reduce body sway as much as possible decreases with increasing age in healthy population [1, 10, 15], as well as in different diseases or trauma [4, 7, 9].

The idealized normal standing posture requires minimal forces to maintain the line of gravity in the centerline of the body controlled by the continuous movements of the hip, knee, and ankle joints. Since the centers of the movement of the joints cannot normally be all brought to coincide with the line of gravity in equilibrium, a broad range of standing stability is being used within which body weight can be shifted and maintained [13, 17]. As a result, coordinated muscle action of the body segments is required since the action of one segment affects the motion of other parts of the body. This latter effect was demonstrated by sagittal perturbation of the standing subject; equilibrium was regained by two different strategies: "ankle strategy", in which muscular forces rotate the body around the ankle joint, or the "hip strategy" involving flexion at the hip and knees [14].

A single force platform is often used to evaluate standing sway characteristics in disabled and healthy [2, 5, 6, 19]. In this method, the subject is standing with both legs on the platform while excursion of the center of pressure or ground reaction forces (GRF) are being monitored.

The obtained measurements express the vectorial sum of the forces acting on both feet. Thus, in those cases where the forces act in both feet oppositely to each other, the resulting sum consists of a very small net force (e.g. lateral) which is often within the noise level of the measurements [4]. In previous studies, single forceplate have nevertheless been used, possibly due to the fact that two forceplates were not available. Various methodologies were suggested. For instance, the anteroposterior/mediolateral (AP/ML) center of pressure amplitude ratio in standing was studied and used to identify subjects possessing neurological deficits from normal subjects. It was shown that the AP amplitude in normals are larger than the ML ones by a ratio approximating 1.5 under both, vision and no-vision conditions. Nevertheless, this ratio calculated in mentally retarded subjects (0.9) was significantly smaller [18].

The ability to maintain standing balance, as also reflected by the measured levels of AP and ML forces, differs considerably among normals. Therefore, conclusions drawn from absolute values of AP and ML forces are only of relative importance, especially when measured with a single platform: the normal pattern of the horizontal reaction forces during standing is characterized by smaller ML forces since the supporting area in the ML direction is larger when standing with feet separated. Under such a condition, the normally obtained AP/ML ratio is greater than 1. Thus, this ratio, especially when calculated individually for each leg, might enable us to detect existing differences between leg activities and to characterize the pattern of acting forces in an affected limb.

Bilateral force measurements are especially significant in the disabled population, where the contribution of each limb separately in the process of balance control is of great interest. Generally, it can be assumed that the information on the single limb GRF is crucial in persons with asymmetrical physical ability such as hemiparetics and amputees.

The present study is part of a more general and ongoing research in which the bilateral reactive force patterns during postural sway activity in normal and pathological subjects are being characterized and analyzed [7, 9, 10, 11]. The specific objective of this paper was to analyze the tangential forces during standing, namely the AP and ML forces, as measured bilaterally and simultaneously. Values of the AP/ML ratios were studied in healthy persons as well as in hemiparetics and below-knee (BK) amputees.

Subjects and Methods

Subjects

Fifty male volunteers participated in this study. The subjects were divided into three groups as follows: 1) Nineteen below-knee amputees with an average age of 63.7 ± 7.2 years (range 54-78 years). Eleven had a left lower limb amputation and eight had an amputation of the right lower limb. They were all good users of their prosthesis in daily life. 2) Twenty two hemiparetics with an average age of 62.8 ± 7.7 years (range 56-77 years). Eight had weakness of the right limbs and fourteen of the left limbs. 3) Nine healthy men (mean age 65.6 ± 8.6 years, range 53-81 years) served as controls.

All volunteers were examined clinically and their medical histories were taken. Healthy and amputees subjects with orthopaedic or neurological problems or disease known to affect equilibrium, were excluded from this study. To establish integrity of equilibrium in the tested subjects, a preliminary Romberg test [5] was conducted. Those who failed to maintain equilibrium during the test were excluded from the study as well.

Instrumentation

Two Kistler Z-4305 platforms were used to evaluate postural sway. These force plates were collaterally installed for adjacent positioning of both feet during standing. The foot-ground reaction forces in the anteroposterior (AP) and mediolateral (ML) directions were simultaneously monitored for both feet during the test. The force signals from the Kistler amplifiers (type 9803), with gains set at 5N/V for the AP and ML directions were routed to an on-line IBM PC through a multichannel Analog to Digital (A/D) converter at a sampling rate of 50Hz. The force traces obtained included transient, slow (approximately 0.1 Hz) above which more rapid (1 Hz and higher) oscillations were superimposed. A numerical procedure was set to rectify these rapid oscillations and to compute their average amplitudes. The transient oscillations served as a baseline. To allow comparison between the different tests, legs and subjects, the obtained averages were normalized to the body weight of each of the subjects and expressed in percentage of body weight (%W).

Procedure

The measurements of foot-ground forces were performed with the subject standing with one leg on each force plate. Since the usage of two platforms impose the evident restriction that each foot should be positioned within the effective measuring area of each platform, an opening of 30 cm between the feet with 20° angle from the axes of each other was indicated in our experiments. The subject was asked to stand relaxed, arms hanging at the sides. The test lasted for 35 seconds of which only the data from the middle 25 seconds were analyzed to avoid the "edge effect" of the test. There were two different testing conditions. In the first test, the subject stood with eyes open, gazing at a fixed target three meters in front of him at eye level. The second test was done with eyes closed.

Statistical analysis of the significance of the results was done by paired t-test and p-value was set at 0.05.

Results

Means and standard deviations for the AP and ML forces for all three groups are shown in Tables 1 and in Table 2, respectively. We compared the affected with the sound limb in the amputees and hemiparetics, as well as the right with the left limb in the healthy subjects when standing with and without vision. In the BK amputees, both the difference between the AP forces (Table 1) in the affected and sound leg obtained in eyes open position, and the difference between the affected and sound obtained in eyes closed position, were found significant (p 0.05). In hemiparetics, both the difference between the affected and sound obtained in eyes open position, and the difference

*Table 1. Mean and SD values of AP forces (% body weight) obtained in the three groups. * significant at the 1 % level (p < 0.01). ** significant at the 5% level (p < 0.05). NS = not significant.*

Subjects	OPEN EYES Affected limb	OPEN EYES Sound limb	p	CLOSED EYES Affected limb	CLOSED EYES Sound limb	p
BK amputees	0.048 ± 020	0.160 ±089	*	0.070 ±040	0.236 ± 115	*
Hemiparetics	0.057 ± 026	0.088 ±041	**	0.096 ±058	0.142 ±071	**
Healthy (R/L)	0.039 ± 019	0.041 ± 013	NS	0.057 ± 028	0.055 ± 024	NS

Table 2. Mean and SD values of ML forces (% body weight) obtained in the three groups. The difference between the two legs was insignificant at the 5% level (p 0.05) in all the tested groups. NS = not significant.

Subjects	OPEN EYES Affected limb	OPEN EYES Sound limb	p	CLOSED EYES Affected limb	CLOSED EYES Sound limb	p
BK amputees	0.079 ± 045	0.072 ± 034	NS	0.106 ±062	0.089 ±039	NS
Hemiparetics	0.052 ± 033	0.056 ± 029	NS	0.081 ±063	0.080 ±044	NS
Healthy (R/L)	0.029 ± 011	0.031 ± 012	NS	0.041 ±026	0.039 ±016	NS

between the affected and sound obtained in eyes closed position, were found significant (p 0.05). In healthy subjects, the difference between the right and left limbs both in standing with vision and in standing without vision, were insignificant. The ML forces (Table 2) differences between the affected, and sound limbs in the BK amputees and hemiparetics, and between the right and left limbs in the healthy subjects, in both eyes positions, were insignificant.

The means of AP/ML forces ratios obtained in each limb in the tested subjects are shown in Table 3. Differences between the mean AP/ML ratios of the affected and sound limbs in the BK amputees were significant (p 0.05) in both eyes positions (0.69 ± 28 and 2.38 ± 1.23 eyes open, 0.75 ± 33 and 2.80 ± 1.26 eyes closed). When comparing the BK amputees and the healthy subjects, the differences in AP/ML ratios between any of the amputees' limbs and each of the limbs of the healthy group were found significant (p 0.05). Differences in AP/ML ratios obtained in the hemiparetics and healthy groups in standing with both eyes positions, were insignificant.

Discussion

In the present study we measured standing foot-ground forces in two groups of disabled subjects, BK amputees and hemiparetics, as well as in a matched age group of healthy men. For this purpose we used two force-plates positioned adjacently allowing to evaluate simultaneously each limb separately.

In healthy subjects, differences between both limbs in the AP and ML forces in standing with and without vision, were insignificant. The AP forces measured in the sound limbs of BK amputees and hemiparetics, not as the case with the ML forces, were significantly higher when com-

*Table 3. The AP/ML forces ratios obtained in the 3 tested groups. * The difference between the two legs was significant at the 1% level (p 0.01). NS = not significant.*

Subjects	OPEN EYES Affected limb	OPEN EYES Sound limb	p	CLOSED EYES Affected limb	CLOSED EYES Sound limb	p
BK amputees	0.69 ± 0.2	2.38 ±1.2	*	0.75 ± 0.3	2.80 ±1.2	*
Hemiparetics	1.49 ± 1.0	1.75 ±0.8	NS	1.49 ±0.7	1.95 ±0.9	NS
Healthy (R/L)	1.36 ±0.3	1.38 ±0.3	NS	1.47 ±0.3	1.44 ±0.3	NS

pared with the affected limbs during standing with both eyes positions. These results indicate that most standing balance control is carried out by the sound limb and the main direction of sway activity produced to maintain balance is in the AP plane. These findings confirm also other [2, 4, 11, 18] studies using standing test on healthy subjects which have reported the distribution of sway to be mainly in the AP direction.

The AP/ML forces ratio depends on the position of the supporting feet, while in wide opening ML forces decrease as compared with standing with feet parallel and touching together [2]. The AP/ML forces ratio obtained in our healthy subjects in standing under conditions chosen in this study, were 1.37 ± 3 (Rt/Lt mean, standing with vision) and 1.45 ± 3 (Rt/Lt mean, standing with no-vision). Differences were insignificant. We further used the AP/ML ratio to characterize standing patterns of BK amputees and hemiparetics.

In BK amputees, the difference between ratios was significant when comparing the amputated with the sound limbs. AP/ML forces ratio in the amputated limb was smaller than unity. In fact, it is known that the rigid foot and ankle of the prosthesis impose a higher mechanical stiffness in the AP direction than in the ML direction. Standing under such conditions, the balance maintaining reactions in the sound limb are greater in the AP direction, as reflected also by the high AP/ML ratio of this limb.

In hemiparetics, the AP/ML ratio difference between both limbs was insignificant, although values in the sound limb were greater. We assume that in spite of the presented neurological deficits in the paretic limb inflicted by CVA, sway activity in AP and ML directions in both limbs is not being compromised. However, it should be born in mind that the ratio reflects the averaging procedure as described in the Methods and hence does not reveal short term phenomena. A difference in ratio does exist, presumably due to the large standard deviations, nevertheless it was not significant. It is important to note that the AP/ML ratios of the sound limb in hemiparetics as well as in amputees are greater comparing with the mean ratio for both limbs in the healthy group. Therefore in both disabled groups, the sound limb sway activity in the AP direction is greater than in the healthy group.

In conclusion, The AP forces involved in balance control are significantly larger in the sound limbs as compared with the affected limbs of BK amputees and in hemiparetics patients in standing with and without vision. Patterns of AP/ML forces ratio in amputees show a significant difference between both limbs in standing in both eyes positions. Control of the standing balance reactions are therefore performed mainly by the sound limbs of both BK amputees and hemiparetics.

Rehabilitation programs for amputees and hemiparetics should include exercises for improving involvement of the affected limbs in the process of balance maintenance in standing. A better standing balance and symmetrical limb load will result also in improving other motor functions and activities of daily living as well as in ambulation.

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