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Stability criterion for controlling standing in able-bodied subjects☆

Miloš R. Popović[a,]*, Ion P.I. Pappas[a], Kimitaka Nakazawa[b], Thierry Keller[c], Manfred Morari[a], Volker Dietz[c]

[a]*Automatic Control Laboratory, Swiss Federal Institute of Technology Zurich, ETH Zenthrum/ETL K28 CH-8092, Switzerland*
[b]*Laboratory of Neuromuscular Dysfunction, National Rehabilitation Center for Disabled, Japan*
[c]*Paraplegic Center, University Hospital Balgrist, Switzerland*

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Abstract

A new stability criterion that can be used to assess the standing condition of a subject from center of pressure (CoP) measurements is presented. This criterion can be applied, for example, to control a standing prosthesis, which should allow a paraplegic subject to stand up, sit down and stand safely without using hands for support. Experiments conducted with able-bodied subjects enabled us to establish a relationship between its stability and the subject's CoP position. Four CoP stability zones were identified: high preference, low preference, undesirable and unstable zones. The high preference zone is defined as the area where the CoP is found 99% of the time during quiet standing. The area where the CoP is found during the remaining 1% of the time is called the low preference zone. The undesirable zone is defined as the CoP area where the subject is forced to change posture in order to maintain balance, and the unstable zone is defined as the CoP area in which the subject is forced to step forward, backward or sideways to maintain stability. A general model of the proposed four stability zones was derived, which can be used to compute stability zones a priori for any subject and thus allows one to assess the subject's stability condition from the CoP measurements. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Standing; Center of pressure; Stability; Zones; Control

1. Introduction

This study is motivated by a long-term objective of our group to develop a standing neuroprosthesis. A neuroprosthesis is a device that generates a series of short electrical pulses, which if applied to properly selected muscles and muscle groups can cause motion of otherwise paralyzed limbs or body parts (Popovic et al., 1999). The standing neuroprosthesis is envisioned as a system that will allow paraplegic and spinal cord injured (SCI) subjects to stand up, sit down and to maintain stable quiet standing without using upper limbs for support. To perform stable quiet standing the prosthesis must be able to assess the subject's stability during standing. Therefore, the objective of this study was to develop a quantitative "measure of stability" that can be used to reliably assess the subject's standing condition (see Fig. 1).

One way to observe stability in subjects during quiet and quasi-quiet standing is by measuring the center of pressure (CoP) position relative to the *base of support* (surface area under and between the feet). The CoP can be accurately measured with commercially available sensory systems such as standing platforms, which can become an integral part of the standing neuroprosthesis. Hence, the "measure of stability" proposed in this paper evaluates the CoP position with respect to the support base and in that way estimates the subject's stability during standing.

The analysis of the able-bodied subject's CoP measurements published in Collins and DeLuca (1995a,b) suggests that during quiet standing the able-bodied subject applies both open- and closed-loop control strategies to regulate balance. In particular, it was proposed that the CoP displacements that occur during time intervals shorter than 1 s are open-loop controlled, and the CoP

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* Corresponding author. Tel: +41-1-632-3638; fax: +41-1-632-1211.

E-mail address: popovic@aut.ee.ethz.ch (M.R. Popović).

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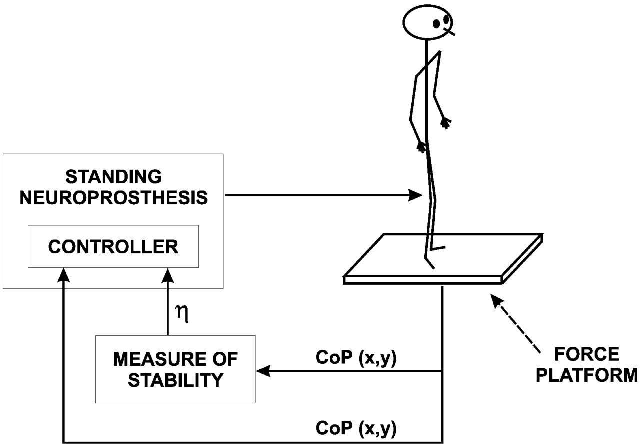

Fig. 1. Control scheme of the "hand-free" standing neuroprosthesis.

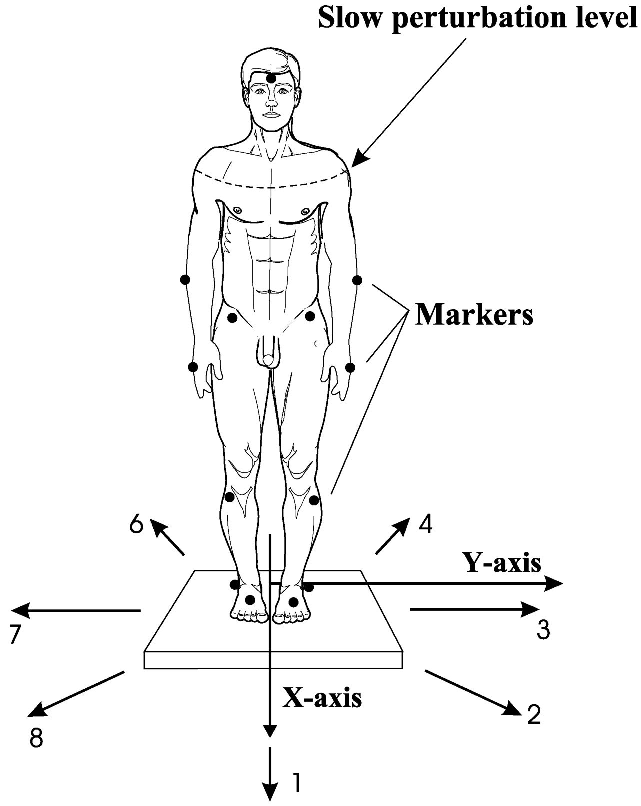

Fig. 2. Subject's initial position and posture during the unperturbed and slow perturbation experiments (black dots represent the Vicon markers).

displacements that take longer time intervals are closed-loop controlled. However, the cited studies do not discuss how one can estimate the subject's stability during standing. In another study published by Henry et al. (1998) the experimental results illustrate how able-bodied subjects control the CoP and the center of mass (CoM) during anterior/posterior and medial/lateral translations. Similar to the previous study, the stability assessment issue is not addressed. A study published by Winter et al. (1998) suggests that the able-bodied subject controls quiet standing by regulating the body stiffness in the anterior/posterior and medial/lateral directions, but does not provide a measure of the subject's stability during standing. In the study published by Matjacic and Bajd (1998a,b), it was assumed that the subject is stable as long as the subject's CoP is within his/hers base of support. The stability margin was evaluated by measuring how close the CoP is relative to the edge of the base of support. Studies by Kamnik et al. (1998) and Riener and Fuhr (1998) investigated different control strategies that can be used to allow SCI subjects to stand up and sit down with a neuroprosthesis. Both studies concentrated on controlling vertical displacement during standing rather than balance. It was left to the subject to maintain balance in the horizontal plane by using the upper body extremities.

Slow perturbation and unperturbed standing experiments were performed with the objective to establish a relationship between the CoP position and the subject's stability condition. The unperturbed standing experiments were used to identify the zones where the CoP of the able-bodied subject can be found during quiet standing. The slow perturbation experiments were used to determine zones where the CoP of the able-bodied subject can be found when the subject is forced to take a corrective action to maintain balance. The results presented in this paper are not in competition with the above-mentioned studies. They rather complement them by proposing a new "measure of stability" suitable to be implemented in a feedback control scheme for hand-free paraplegic standing.

2. Methods

2.1. Experimental setup

The experimental setup consisted of a Kistler's force plate 9366AB, a Kistler's 5017A amplifier, a four camera Vicon 370 motion measurement system, a 230 MHz pentium PC with A/D Lab PC + card and a custom made data acquisition software. The Kistler's force plate was used to measure the subject's CoP position as a function of time with an accuracy of ± 1 mm. The Vicon motion measurement system and 13 markers attached to the subject's body were used to monitor the three-dimensional movements of the subject's body segments with an accuracy of ± 1 mm (see Fig. 2). The motion of the body segments was used to identify changes in the subject's posture during standing and not to calculate the subject's CoM position. The force plate and the Vicon measurements were synchronized and the sampling period for both measurement systems was 20 ms. All measurements and the data analyses were performed in the X and Y coordinate frame shown in Fig. 2. Data measured for different subjects were normalized by dividing x and y CoP coordinates by the subject's feet length. This normalization was chosen because the measured CoP excursions were proportional to the subject's feet length.

During the experiments all subjects were standing still on the force platform, with bare feet and in an upright relaxed position (see Fig. 2). The visual surrounding consisted of plain white walls that were 4.2 m away from the subject. Initially, the subject was asked to choose the most comfortable quiet standing posture, which was recorded by drawing contours on the Kistler's plate around the subject's feet. In subsequent experiments the subject had to stand in these contours to ensure that his/hers feet were positioned with an accuracy greater than $\pm$ 2.5 mm. In general, the subjects had the toeing-out angle between 15 and 35° and the intermaleolar distance between 100 and 170 mm. The quiet standing posture was chosen because it could be easily implemented using a standing prosthesis and is commonly used by similar systems (Kamnik et al., 1998; Riener and Fuhr, 1998). The experiments were performed with three female and seven male able-bodied subjects listed in Table 1. Their average age was 28.6 years and none of the subjects had a history of neurological disease. Informed consent was obtained from all subjects prior to the experiments.

2.2. Unperturbed standing experiments

During the unperturbed standing experiments the subject was asked to stand still for 5 min (see Fig. 2). In order to investigate the influence of fatigue and visual feedback on the subject's standing stability, four different sets of unperturbed standing experiments were performed: (A) subject rested (not tired) and eyes open; (B) subject rested and eyes closed; (C) subject tired and eyes open; and (D) subject tired and eyes closed. The subjects were "fatigued" by standing still for at least 15 min prior to the experiment.

2.3. Slow perturbation experiments

During the slow perturbation experiments the subject, who was rested and had the eyes open, was *slowly* pushed out of equilibrium in one of eight directions indicated in Fig. 2. The perturbation speed was in the range of 1 to 2 cm/s and the subject was pushed only once in each of the perturbation directions. The subject was pushed at the shoulder level with a long aluminum bar until the subject was forced to react by stepping forward, backward or sideways in order to regain stability. Since the perturbations were slow the subjects were able to anticipate the direction and the moment of the disturbance.

2.4. Data analysis

As discussed in the following sections the CoP measurements of the unperturbed and slow perturbation

Table 1
Measured stability zones during quiet standing

No.			1	2	3	4	5	6	7	8	9	10
Subject			B.C.	K.T.	M.D.	M.N.	N.K.	P.I.	P.M.	S.P.	S.R.	W.E.
Sex			F	M	M	F	M	M	M	M	M	F
Age			22	30	24	28	36	28	33	23	29	33
Weight (kg)			52	70	69	70	55	75	76	70	72	68
Height (cm)			157	165	187	160	170	178	185	178	180	172
Feet length (mm)			232	262	286	263	254	276	277	274	287	259
Zone	Fatigued	Eyes	Zone size (mm^2)	Zone size (mm^2)	Zone size (mm^2)	Zone size (mm^2)	Zone size (mm^2)	Zone size (mm^2)	Zone size (mm^2)	Zone size (mm^2)	Zone size (mm^2)	Zone size (mm^2)
High pref.	No	Open	324	328	412	460	327	1163	1981	1434	376	348
High pref.	No	Close	399	352	543	508	369	1248	953	383	657	534
High pref.	Yes	Open	268	282	525	405	314	2047	2619	1316	414	584
High pref.	Yes	Close	331	397	586	430	574	1406	2682	323	520	527
Low pref.	No	Open	10,763	21,751	13,613	12,877	14,534	7280	20,044	3958	16,263	—
Undesirable	No	Open	11,396	15,782	19,197	16,224	11,349	26,126	18,524	31,201	14,027	—

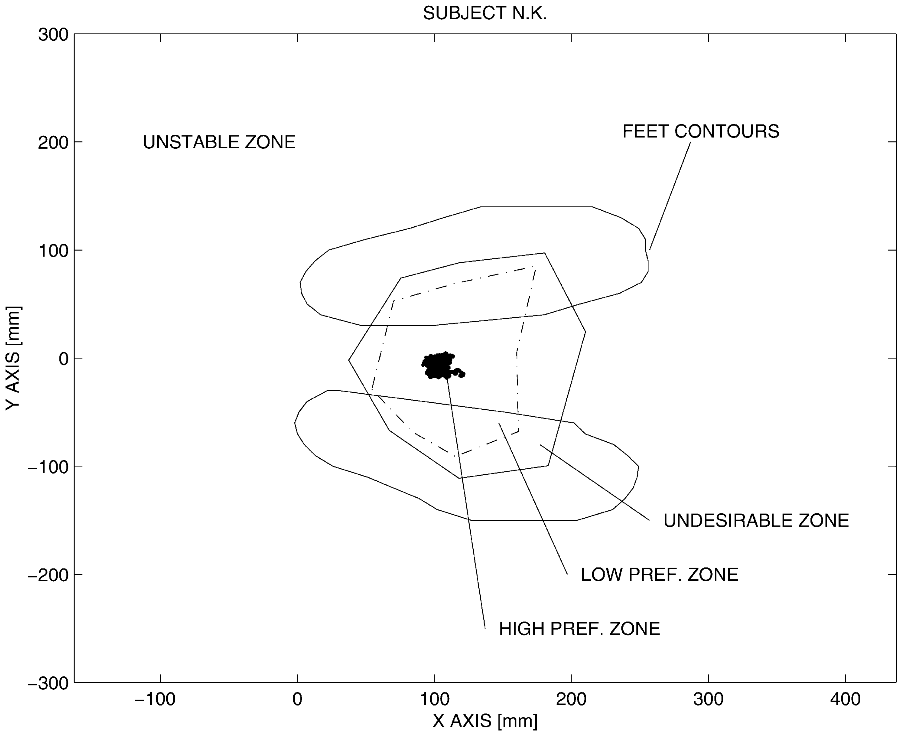

Fig. 3. High preference, low preference, undesirable and unstable zones for subject N.K.

experiments were used to define four different stability zones, shown in Fig. 3. The boundaries between the stability zones were modeled using ellipses since they can capture the two-dimensional form and orientation of the stability zone boundaries. The ellipses were fitted in such a way that they have the same surface areas and the same two-dimensional *moments of inertia* as the surfaces encircled by the measured boundaries (Jain, 1986, pp. 392–394).

3. Experimental results

3.1. Unperturbed standing experiments

The unperturbed standing experiments, performed with all ten subjects listed in Table 1, revealed that during quiet standing the CoP can be found 99% of the time within a very small elliptical area which we called the *high preference zone* (see Figs. 3 and 4). The high preference ellipse was fitted around the measured high preference zone using the *moment of inertia approach* discussed in Section 2.4. In general, the major (larger) axis $d1_{\mathrm{hp}}$ of the high preference ellipse was along the X-axis and was significantly larger than the minor axis $d2_{\mathrm{hp}}$ (see Table 2 and Fig. 5). Since the major axis of the high preference ellipse was along the X-axis (angle α_{hp} between the X-axis and $d1_{\mathrm{hp}}$ was approximately 0°) this indicates that the CoP position varied more along the anterior/posterior axis, compared to the medial/lateral axis. This result suggests that during quiet standing the subjects have higher body stiffness in the medial/lateral direction compared to the anterior/posterior direction. In addition, one can observe that the high preference ellipse is symmetric with respect to the body's median plane. Individual dimensions and statistics of the fitted ellipses around measured high preference zones are provided in Table 2. The mean value of the normalized[1] surface area of the high preference zone was $S_{\mathrm{hp}} = 0.01$ (s.d. 0.008).

To determine the influence of visual feedback and fatigue on the size of the high preference zone, the unperturbed standing experiments were performed when the subjects were fresh, fatigued and when their eyes were open and closed. The hypothesis was that visual feedback and fatigue influence the size of the high preference zone. The hypothesis was tested by comparing the sizes of the high preference zones obtained from the experiments A, B, C and D discussed in Section 2.2. The following experimental results were compared: (1) A and B; (2) A and C; (3) A and D; (4) B and D; and (5) C and D. The test was done using the *nonparametric signed rank test* (Rice, 1995) because the data tested did not have a normal probability distribution function. Tests (2) and (4) showed that the difference between the high preference zones for fatigued and non-fatigued subjects was non-significant ($p > 0.05$). Test (3), which analyzed the combined influence of visual feedback and fatigue on the size of the high preference zone, was non-significant

[1] The stability zone surfaces were normalized by dividing the actual surface area by the squared length of the subject's feet.

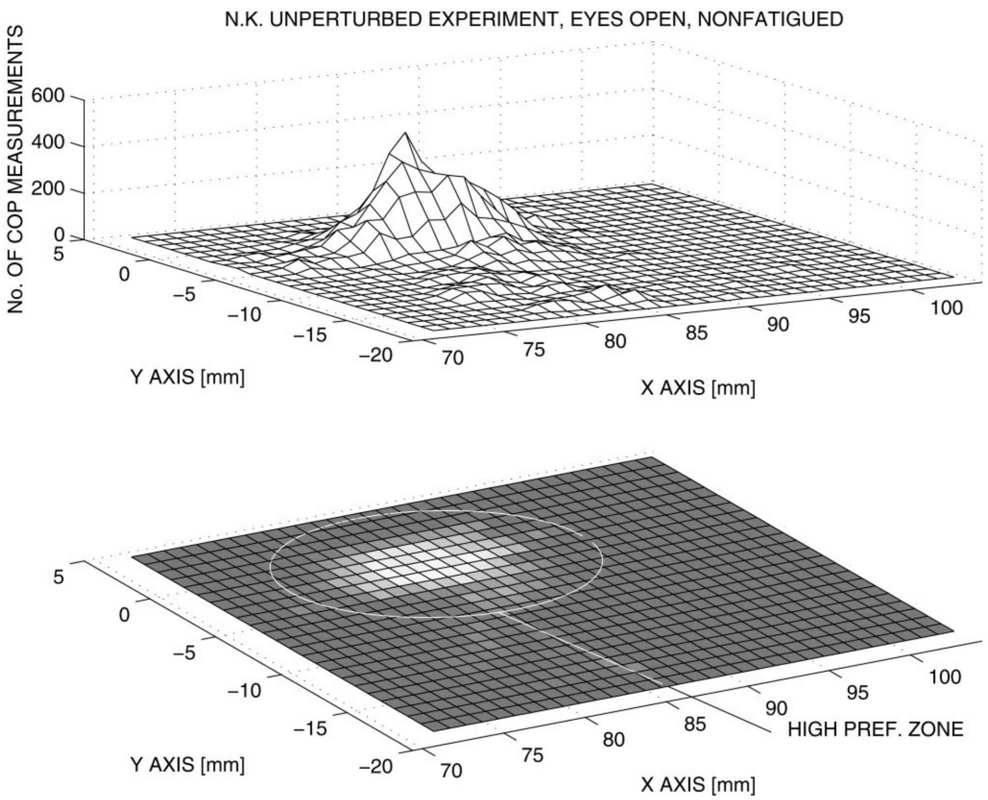

Fig. 4. 3D histogram of N.K.'s high preference zone shown in Fig. 3 — eyes open and subject was not fatigued.

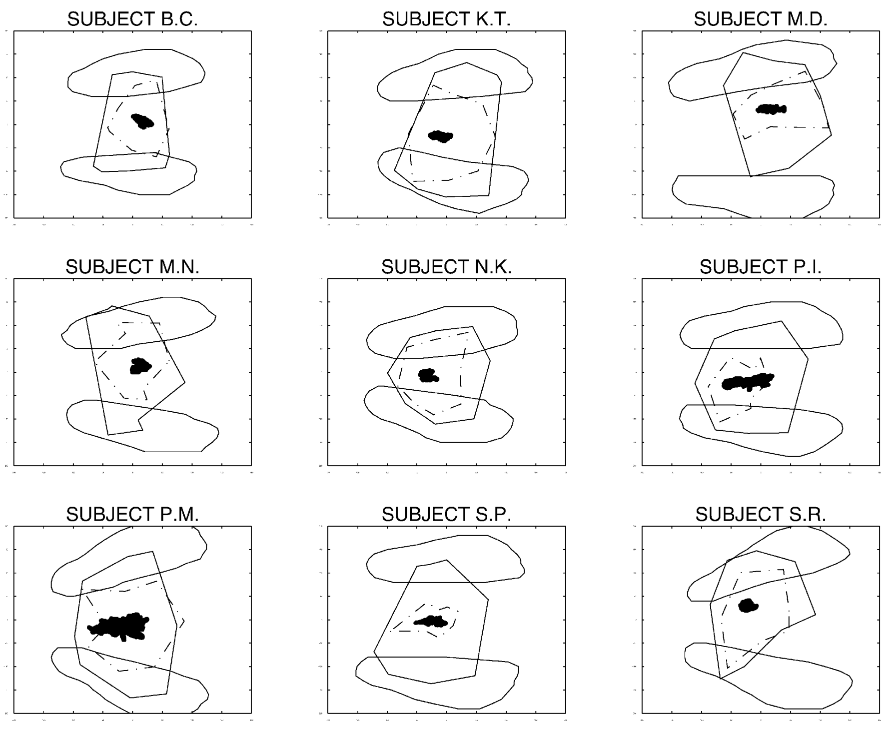

Fig. 5. High preference, low preference, undesirable and unstable zones for various subjects.

Table 2
Normalized dimensions of the high preference, low preference and undesirable ellipses

No.		1	2	3	4	5	6	7	8	9	10		
Subject		B.C.	K.T.	M.D.	M.N.	N.K.	P.I.	P.M.	S.P.	S.R.	W.E.	Mean	S.D.
	$d1_{hp}$	0.119	0.123	0.134	0.128	0.142	0.278	0.303	0.164	0.119	0.156	0.162	0.068
	$d2_{hp}$	0.063	0.053	0.063	0.066	0.052	0.092	0.120	0.081	0.073	0.068	0.073	0.026
High pref.	α_{hp} (°)	−17.1	0.5	−1	15.1	16.6	6.2	0.6	6.9	−22.3	−4.4	2.3	21.4
	x_{hp}	0.552	0.403	0.614	0.487	0.403	0.406	0.442	0.428	0.366	0.777	0.486	0.121
	y_{hp}	0.034	−0.083	0.139	0.058	−0.035	−0.082	−0.053	−0.012	0.108	−0.078	0.003	0.087
	$d1_{lp}$	0.662	0.761	0.390	0.622	0.672	0.470	0.680	0.221	0.690		0.574	0.177
	$d2_{lp}$	0.396	0.538	0.565	0.394	0.437	0.306	0.545	0.370	0.375		0.436	0.092
Low pref.	α_{lp} (°)	87.6	80.6	110.5	76	81.7	66.4	87.7	102.9	72.4		85.1	14.1
	x_{lp}	0.560	0.456	0.648	0.451	0.456	0.334	0.503	0.418	0.400		0.469	0.092
	y_{lp}	0.040	−0.105	0.127	0.107	−0.011	−0.121	−0.048	−0.008	0.055		0.004	0.087
	$d1_{u}$	1.004	1.158	0.896	1.015	0.811	0.889	1.107	0.968	0.886		0.970	0.113
	$d2_{u}$	0.530	0.607	0.580	0.536	0.638	0.653	0.613	0.631	0.537		0.597	0.048
Undesira.	α_{u} (°)	85.5	79.8	98.1	96.1	86.1	81.4	92.98	79.3	71.6		85.7	8.7
	x_{u}	0.503	0.491	0.605	0.420	0.508	0.434	0.462	0.454	0.404		0.476	0.061
	y_{u}	−0.010	−0.081	0.086	0.041	−0.018	−0.060	−0.056	−0.060	0.098		−0.007	0.067

($p > 0.05$). Test (5), which analyzed the influence of visual feedback on the size of the high preference zone when the subject was fatigued, was non-significant as well ($p > 0.05$). Only test (1), which analyzed the influence of visual feedback on the size of the high preference zone when the subject was fresh, showed that the difference was significant ($p < 0.05$). Since tests (3) and (5), which also examined the influence of the visual feedback on the high preference zone size, were non-significant we concluded that in our experiments the visual feedback did not contribute to the control of balance. This can be attributed either to the relatively limited number of subjects that participated in the study or to the visual surrounding subjects were exposed to during experiments. Note that in some subjects it was observed that fatigue and lack of visual feedback influenced the size of the high preference zone (see Table 2), but this was not the case with majority of the subjects that participated in the study.

3.2. Slow perturbation experiments

The slow perturbation experiments were performed with all subjects listed in Table 1 except with subject W.E. In all subjects that participated in the experiment, it was observed that when the subject was slightly pushed, the subject neither changed the body posture nor made an apparent body motion aimed at compensating for the disturbance, although his/hers CoP was out of the high preference zone. When the disturbance was terminated the subject immediately moved the CoP back into the high preference zone. During quiet standing the CoP can be found 1% of time in this zone, which we called the *low preference zone* (see Fig. 3). If the subject was pushed further he/she reacted by first lifting toes or heels for 3 to 4 mm along the vertical axis. If the subject was pushed from the front the toes were lifted, and following a push from the back the heels were lifted. Hence, lifting of toes or heels was used as an indication that the CoP left the low preference zone and entered a new zone which we called the *undesirable zone* (see Fig. 3). Only after the subject's toes or heels were lifted the subject used the arms and body posture to compensate for the disturbance and bring the CoP back into one of the preference zones. The slow perturbation continued until the subject reacted by stepping forward, backward or sideways in order to regain stability. This reaction to the disturbance was used as an indication that the CoP entered a new zone which we called the *unstable zone* (see Fig. 3). Note that during the experiments we were only interested in a slow disturbance of the CoP. Once the subject made a step forward, backward or sideways the CoP was not measured any more.

The slow perturbation experiments showed that the low preference and undesirable zones were spread along an axis parallel to the Y-axis, unlike the high preference zone that was spread along the X-axis. In other words, the ellipses' orientation angles α_{lp} and α_u between the X-axis and the major axes of the low preference and the undesirable ellipses, respectively, clustered around 90°. Individual dimensions and the statistics of the low preference and undesirable ellipses that were fitted around the low preference and undesirable zones, respectively, are presented in Table 2. Note that in all subjects major $d1_{lp}$ and minor $d2_{lp}$ axes of the low preference ellipses were of the same order of magnitude, while the major axis $d1_u$ of the undesirable ellipses was significantly larger than the minor axis $d2_u$.

The surface of the low preference zone was calculated as the area between the high preference and low preference ellipses, and the surface of the undesirable zone was calculated as the area between the low preference and the undesirable ellipses. The remaining part of the standing surface represents the unstable zone. The mean values of the areas of the normalized surfaces of the low preference and the undesirable zones were $S_{lp} = 0.19$ (S.D. 0.08) and $S_u = 0.25$ (S.D. 0.08), respectively. Note that the areas of the low preference and undesirable zones were significantly larger than the area of the high preference zone (see Table 1 and Fig. 3).

An important result that came out of the slow perturbation experiments is that in all subjects the outer boundary of the low preference zone (low preference ellipse) was always smaller than the base of support (see Fig. 5). This result indicates that the assumption made by Matjacic and Bajd (1998a,b) and others, that the subject is stable during quiet standing as long as the CoP is in the subject's base of support, is not entirely correct. Instead, in order to stand safely and comfortably the subject must have the CoP in the high or low preference zone, which combined surface area is approximately equal to 30% of the subject's base of support.

4. Modeling

In this section the above experimental results will be used to derive a generic physiological model that will be used to define a priori stability zones for paraplegic subjects. Based on this model a quantitative "measure of stability", which can be used in a feedback control system for paraplegic standing, will be proposed.

4.1. Model of the stability zones

To obtain a generic model of the stability zones the parameters of the boundary ellipses, obtained for each subject, were averaged (see Table 2). The averaged values of the centers of the high preference, low preference and undesirable ellipses clustered around the coordinate $(x, y) = (0.47,0)$. To simplify the model it was assumed that all three ellipses have a common center. This hypothesis was tested using the *nonparametric signed rank test* (Rice, 1995) and was shown that the differences were non-significant ($p > 0.05$). Similarly, the average orientation angles of the high preference ellipse α_{hp}, the low preference ellipse α_{lp} and the undesirable ellipse α_u were approximately 0, 90 and 90°, respectively. In order to further simplify the model of the stability zones we tested the following hypotheses: that the population mean of angle α_{hp} was 0°; that the population mean of angle α_{lp} was 90°; and that the population mean of angle α_u was 90°. As before, the *nonparametric signed rank test* showed that the differences were non-significant ($p > 0.05$).

Table 3
Model of the normalized high preference, low preference and undesirable ellipses

Zone boundaries	$d1$	$d2$	α (°)	x	y
High preference	0.16	0.07	0	0.47	0
Low preference	0.57	0.43	90	0.47	0
Undesirable	0.97	0.59	90	0.47	0

The above analysis lead to the following conclusions. Without making a statistical error, one can assume that all three boundaries of the stability zones have a common center placed on the median line at 47% of the feet length starting from the heels toward the toes ($(x, y) = (0.47,0)$). Also, one can assume that the high preference ellipse's orientation angle α_{hp} is equal to 0°, and that the low preference and the undesirable ellipses' orientation angles α_{lp} and α_u, respectively, are equal to 90°. Using these assumptions and the average values of the major and minor axes of the stability ellipses, the following model of the stability zones was derived:

$$\begin{aligned}
&\text{high preference zone} && \frac{(x-0.47)^2}{d1_{hp}^2} + \frac{y^2}{d2_{hp}^2} < 1,\\
&\text{low preference zone} && \frac{(x-0.47)^2}{d1_{hp}^2} + \frac{y^2}{d2_{hp}^2} \geqslant 1\\
&\quad \text{and } \frac{(x-0.47)^2}{d2_{lp}^2} + \frac{y^2}{d1_{lp}^2} < 1, &&\\
&\text{undesirable zone} && \frac{(x-0.47)^2}{d2_{lp}^2} + \frac{y^2}{d1_{lp}^2} \geqslant 1\\
&\quad \text{and } \frac{(x-0.47)^2}{d2_{u}^2} + \frac{y^2}{d1_{u}^2} < 1, &&\\
&\text{unstable zone} && \frac{(x-0.47)^2}{d2_{u}^2} + \frac{y^2}{d1_{u}^2} \geqslant 1,
\end{aligned} \tag{1}$$

where x and y are CoP coordinates, and $d1_{hp}$, $d2_{hp}$, $d1_{lp}$, $d2_{lp}$, $d1_u$ and $d2_u$ are constants provided in Table 3. Model (1) is also illustrated in Fig. 6. In Fig. 7, the measured and the modeled dimensions of the major and minor axes of the stability ellipses are presented. This figure indicates that the proposed model adequately describes the experimental results and shows that the applied normalization was appropriate.

4.2. Measure of stability

As mentioned earlier, our objective is to develop a neuroprosthesis that will allow a paraplegic subject to

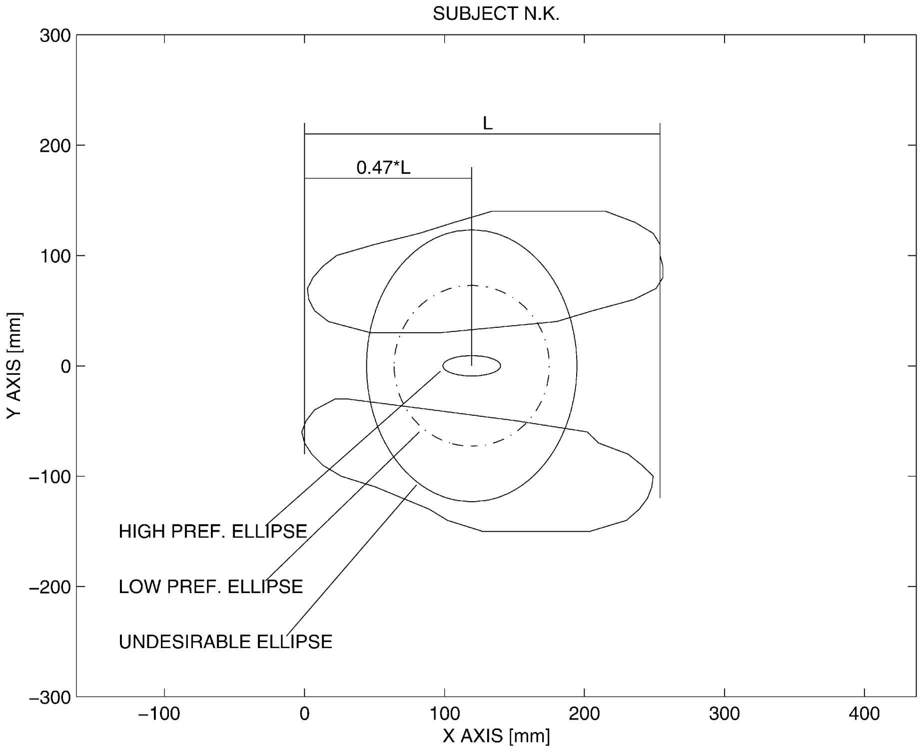

Fig. 6. Model of the high preference, low preference, undesirable and unstable zones for subject N.K.

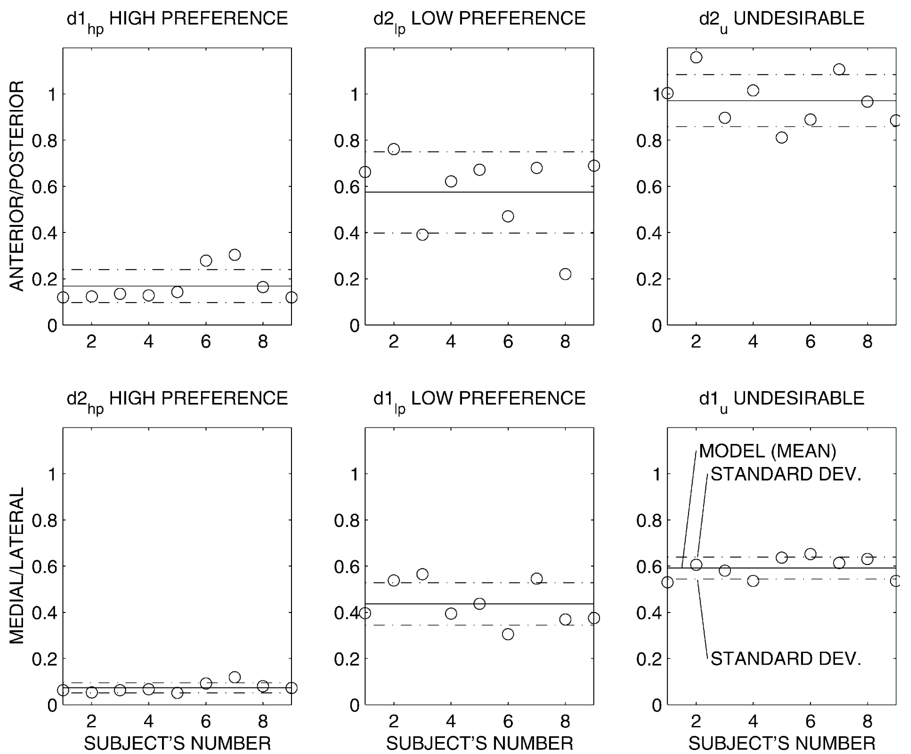

Fig. 7. Dimensions of the measured and modeled axes of the stability ellipses for each subject (solid lines are modeled (mean) dimensions, circles are measured dimensions and dashed lines are standard deviations).

stand safely without using hands for support. A typical paraplegic subject that would benefit from such a prosthesis has reduced or no control over the legs, abdominal muscles and lower back muscles. Therefore, such a subject cannot change posture nor reposition feet to compensate for a disturbance (the upper extremities are also excluded since the subject will use them to manipulate objects during standing). Therefore, a "hand-free" standing prosthesis that will provide safe and comfortable standing must guarantee that the CoP is always maintained inside the high and low preference zones. Preferably, the CoP should be maintained in the high preference zone since the CoP positions in the low preference zone that are close to the low preference ellipse are only marginally stable.

Using model (1) and the subject's feet size one can define a priori stability zones for any paraplegic subject. In addition to model (1), a numerical parameter η, which is a function of the CoP position and represents a physiological "measure of stability" (2), was defined. When the CoP is in the high preference zone η is equal to zero and when the CoP is within the low preference zone η increases linearly from zero to one as the CoP moves away from the high preference zone (see Eq. (2)). When the CoP is in the undesirable or unstable zone η is equal to 1.

$$\eta = \begin{cases} 0 & \text{for } \frac{(x-0.47)^2}{d1_{hp}^2} + \frac{y^2}{d2_{hp}^2} < 1 \\ 0 \leqslant \eta(x,y) < 1 & \text{such that } \frac{(x-0.47)^2}{((d2_{lp}-d1_{hp})\eta + d1_{hp})^2} + \frac{y^2}{((d1_{lp}-d2_{hp})\eta + d2_{hp})^2} = 1 \\ 1 & \text{for } \frac{(x-0.47)^2}{d2_{lp}^2} + \frac{y^2}{d1_{lp}^2} \geqslant 1 \end{cases} \tag{2}$$

A standing prosthesis controller that would use the "measure of stability" η to maintain stable quiet standing should operate as follows (see Fig. 1). When η is equal to zero the controller should have the objective to maintain the CoP in the high preference zone. When the parameter η becomes greater than zero the controller should have the objective to reduce η by moving the CoP back into the high preference zone. The larger the parameter η, the stronger is the control action of the prosthesis. Event $\eta = 1$ will have to be avoided by the controller because it would mean that the subject with the prosthesis is unstable.

The proposed "measure of stability" parameter is one of several examples how the CoP stability zones and model (1) can be used in practical applications. Other applications such as assessment of the subject's balancing capabilities during quiet standing, or monitoring changes in the subject's stability zones after stroke or spinal cord injury will be pursued in the future.

5. Conclusions

In this paper we introduced a new "measure of stability" that assesses the standing condition of a subject during quiet standing using CoP measurements, which can be obtained with standard pressure sensing platforms. The proposed "measure of stability" compares the CoP measurements with the experimentally obtained stability zones: *high preference*, *low preference*, *undesirable* and *unstable zones*, and provides a quantitative measure of the subject's stability condition. The "measure of stability" ranges from zero to one, where zero represents stable standing and one an unstable standing condition. If the CoP is within the high preference zone the "measure of stability" equals zero. Within the low preference zone it increases linearly from zero to one as the CoP moves away from the high preference zone. In the undesirable and unstable zones the "measure of stability" equals one, which indicates that the subject is unstable and needs to move the upper or lower limbs to regain stability. This study also showed that it is not sufficient for a subject to have the CoP positioned within the base of support in order to stand safely and comfortably. Instead, the subject's CoP has to be inside the high and low preference zones, when combined surface area is approximately equal to 30% of the subject's feet base.

This study inevitably raises a number of questions. For example, in this study only slow perturbations have been used to identify the stability zones. Thus, the subjects were able to anticipate the direction of perturbation and the moment when the perturbation will occur. Whether or not the stability zones would have the same shapes and sizes if the perturbations were fast and their directions unknown to the subject, remains to be answered. It is also possible that the stability zones would have different shapes for different feet positions. Since the subject population in this study was limited it would be also of interest to once more investigate impact of the visual feedback and fatigue on the shapes and sizes of the stability zones using a larger population of subjects. Nevertheless, the results presented in this paper add a new component to the study of balance and control of stability during standing. They introduce the concept of stability zones, which we expect to have an impact on the design of standing prostheses. The proposed "measure of stability" is suitable to be implemented in a feedback control scheme to assess and maintain the subject's stability during standing.

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