ANALYSIS OF MODES OF QUIET STANDING IN NEUROLOGICALLY INTACT HUMAN SUBJECTS

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ABSTRACT: The purpose of this study was to characterize the possible modes of quiet standing with respect to the ground reaction vector (GRV) and the biomechanical configuration of the human body in the sagittal plane. A three-link model of the body was used. For any possible standing posture, one can specify the distance between the GRV and the centers of rotation of the hip, knee, and ankle. This model has eight possible modes of standing, as defined by the sign of the distance between the GRV and joint center of rotation for each joint. Subjects stood on a biomechanics platform to measure the GRV. The position of the joint centers of rotation (as approximated by surface landmarks) were recorded by a precision differential pulley system. From the raw data, a stick figure representation was later reconstructed, and the mode of standing at each sampling instant was calculated. A detailed comparison was made of the GRV predicted by the orientation of the three-link model and the actual GRV measured by the biomechanics platform. During quiet standing, most subjects choose only one or two modes of standing, and even though postural sway is occurring, maintain postures which use these modes. Between subjects, different modes of standing are seen, however, there are three modes that are used almost exclusively by all subjects. This information may be of use in attempting to restore quiet stance in paraplegic individuals by electrical stimulation.

KEYWORDS: Posture, Standing, Human, Biomechanics, Orthopaedics, Neural Prostheses

INTRODUCTION

Biped stance is an activity different from various support phases of the gait cycle, movement from a sitting to standing position, and quadruped standing. These distinctions are critical in defining the scope of this paper, and in raising precautions when attempting to make comparisons with data from previous studies on these related topics. Studies of the biomechanics of stance have typically attempted to quantify either the positions of the body segments or the behavior of the ground reaction force or ground reaction vector (GRV). Relatively few studies of stance have stressed the need to measure both of these quantities simultaneously.

Qualitative assessment has been the most popular clinical approach to document posture. A patient with postural disorders may be tested for a positive Romberg sign. The simplest way of quantifying standing performance is still photography with a plumb line [1]. Deviation of body markers from the plumb line can be measured. Admittedly, this approach samples only one postural state, and quiet standing is not truly static, yet such photography is useful in quantifying gross abnormalities.

Measurements of weight bearing in the legs and postural sway have also been utilized to quantify standing performance. During quiet stance, most sway occurs in the AP direction. Many studies have measured the behavior of the center of pressure within the base of support provided by the feet, with various types of force platforms [2,3,4,5,6]. A rather strong case for the clinical utility of quantitative documentation of the behavior of the ground reaction vector has been made [5,7].

Techniques have been proposed for measuring the position of the body segments during gait and various other movements and postures. A number of electrogoniometers have been proposed [8,9,10]. These all require extensive external attachment to the body. While these devices all have good dynamic accuracy, their static calibration is often difficult, and the baseline (DC level) can shift if the external attachments slip. Body segment positions have also been measured by techniques which depend on external body markers, either reflective, light emitting, or sonic emitting [11,12,13,14]. Accuracy over small ranges for such devices may not be optimal.

There has been some controversy over the degree of complexity needed when modeling quiet stance. A variety of models have been proposed for human standing, ranging from simple, single-link models to complex multi-link models [15,16]. While studies restricted to the behavior of the ground reaction vector within the base of support or the position of the body segments do have some clinical relevance, it is not possible to uniquely specify the postural configuration present without combined force and body segment position information. This is because more than one posture can produce a given ground reaction vector. Reconstruction of the GRV based on body segments should be verified by actually measuring the GRV [17].

During stance, the literature suggests that the regulated variable is the position of the ground reaction vector within the base of support provided by the feet. This simply means that while a great variety of combinations of body segment positions are possible during stance, these combinations always occur in such a way that the ground reaction vector is kept within a narrowly defined range. The behavior of the system can be adequately described by relating the position of the body segments and ground reaction vector.

Muscle activation must occur in a manner compatible with the biomechanical configuration. It is not yet clear whether the muscle activation determines the biomechanical configuration or the biomechanical configuration determines the muscle activity. The majority of disagreements between studies of stance especially with respect to muscular activation can be attributed to a failure to adequately document subtleties in biomechanical configuration. The literature suggests that there are a variety of biomechanical configurations or "set points" which the body may assume during quiet standing, both within and between individuals. In nearly all of these configurations, the postural control system is able to adequately regulate the ground reaction vector about the set point. One concern of this paper is how the selection of operating point is accomplished.

The reasons for the apparent lack of success in describing quiet standing may be due to the fact that this is a very complex sensorimotor act, and without a theoretical basis to use in choosing and interpreting quantitative measurements, efforts to simply quantify various aspects of standing based on too few variables may be fruitless. The long term goal of these studies is to establish a quantitative theoretical model for the act of quiet standing with clinical relevance for restoring the standing function in neurologically impaired individuals [18,19].

METHODS

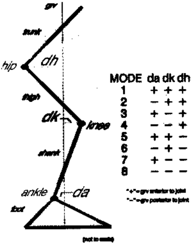
Models of Standing: A three-link model has been developed, as shown in figure 1, which allows the user to input to the program the dimensions of the foot, body segment lengths (shank, thigh, and HAT [head arms trunk]), and centers of mass for each segment. The mass distributions of the segments were taken from previously published data [20]. The center of mass of each segment was assumed to be at the center of the link, except for the trunk, which was taken at 0.45 of the link length. The model is restricted to movement in the antero-posterior plane, and provides information regarding the distance between the ground reaction vector and the joint centers of rotation. This information forms the basis for defining the modes of standing. With three joints being considered, the GRV may be either in front of or behind a joint. When all such possible combinations of signs are considered, eight possible modes of standing are defined, as shown in figure 1.

In the experiments, model inputs are the positions of the joint centers of rotation (knee and hip) and the shoulder of the trunk segment of a human subject in real time (as measured by the apparatus described below). The model also acquires data from the biomechanics platform to allow computation of the actual GRV. The model is then able to compare the GRV calculated from the postion of the body segments with the GRV observed on the force plate.

The ground reaction vector was measured with a conventional force plate (Advanced Mechanical Technology, Incorporated model OR6-5-1). This device measures three orthogonal forces and moments about three orthogonal axes. The axis convention used was antero-posterior, y axis; lateral, x axis; vertical, z axis. The shear force in the antero-posterior direction (F_y) was monitored and found to be insignificant during these experiments In this study lateral forces and moments were observed but not recorded.

There are fundamental problems in static calibration in either joint angle or body segment position measurement [9] This is due to three major factors. First, the articulating joints are buried beneath soft tissue; second the joints typically move in more than one degree of freedom; and third, the location of the instantaneous center of rotation in a given degree of freedom may vary with joint position. It is not possible to fully overcome these factors if one is restricted to non-invasive measurement systems and cannot use radiological techniques.

Since attention is being restricted to movement in the



MODE	da	dk	dh
1	+	+	+
2	–	+	+
3	+	–	+
4	–	–	+
5	+	+	–
6	–	+	–
7	+	–	–
8	–	–	–

"+" = grv anterior to joint
"–" = grv posterior to joint

FIGURE 1: Three link model. Modes of standing are defined by the sign of GRV to joint center of rotation distance.

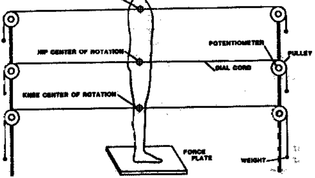


FIGURE 2: Schematic diagram of position measuring system. See text for details of differential potentiometers.

antero-posterior directions a simple, but accurate and reliable, position sensing device was used. In this particular application, this device is a satisfactory low-cost alternative to more sophisticated schemes when measurements are being made on neurologically intact individuals during standing when movements are small [21].

Two single turn precision servo potentiometers were used to measure translation of each point of interest in the y direction, as shown in figure 2. The outputs of the potentiometers are differentially amplified to reject movements in the lateral and vertical directions. Only movements in the horizontal (A-P) direction are monitored. Non-elastic cord ("Dial cord") and pulleys are used to rotate the potentiometers. Attachment of the measuring cord to the subject is accomplished by securely taping a small clip (Pomona Electronics "minigrabber") to the subject with the point of clasping over the center of the appropriate anatomical marker. Once a static calibration is achieved, the attachment can be made to the subject, as shown in figure 2.

The alignment procedure for the measurement system consists of utilizing plumb lines placed approximately 15 cm laterally to the force plate, one on each side. These plumb lines are placed so that they lie precisely on the x-axis of the force plate. When a subject is being studied, great care is taken to align the axis of rotation about the ankle exactly with the x axis of the force plate. The body segment measuring system may then be zeroed and calibrated using the plumb lines and a moveable scale. These position measurements, when combined with the measured segment lengths enable computation of joint angles. The three quantities measured were the y (antero-posterior) coordinates of the knee center of rotation (y_k), the hip center of rotation (y_h), and the shoulder position (y_s).

Data Aquisition and Reduction: The data from the two systems described in the previous sections (force plate, body segment position measurement) were combined by one data aquisition system. Five channels of information were digitized: 1) the moment about the x-axis of the force plate (M_x), 2) the vertical force component (F_z), 3) knee center of rotation (Y_k), 4) hip center of rotation (Y_h), and 5) shoulder position (Y_s). This information was digitized at a rate of 20 samples per second per channel for periods up to 24 minutes. From the digitized data, plots were prepared of each of the channels over time, and at any desired instant in time, a stick figure could be obtained showing the ground reaction vector and position of the body segments.

Since the position of the ankle was known and constant, and the body segment parameters (distance between joint centers of rotation ankle-knee, knee-hip, and hip-shoulder) can be measured, this information can be combined with the y-coordinate of the center of pressure to obtain a complete description of the body segment positions and ground reaction vector using simple trigonometry. [Note: Measurements indicate that during quiet standing the ground reaction vector (in the A-P plane) does not deviate more than about 0.3 degrees from parallel with the gravity vector. This is distinctly different from gait and perturbation studies, where large deviations in both magnitude and angle of the ground reaction vector are observed. This method is, therefore, applicable to studies restricted to quiet stance and slow sway.]

Human Subjects: Twelve subjects participated in this research protocol, which was approved by the IIT Institutional Review Board. Subjects reported no neurological problems and were not taking any medications. Subjects wore shorts and stood on the force platform barefooted, with comfortable positioning and lateral spacing of the feet. The subjects were instructed not to move their feet during the experiment. The position measuring system was attached to appropriately determine locations on the surface of the skin with medical adhesive tape. No subjects reported adverse reaction to the tape, dizziness while standing or any other problems.

Experimental Protocol: Data were collected under three different conditions, as described below
Condition 1: Subjects stood in their most comfortable, relaxed position with arms crossed in front of chest for a period of 80 seconds. Condition 2: They were to slowly sway about the ankles between as far forward and backward as possible without raising the heels or toes, and without feeling unstable, for a period of 80 seconds. Condition 3: Same as condition one, but stand for 22 minutes and 40 seconds.

RESULTS

The strategy matrices for each condition are shown in table 1. These show the percent time spent at each mode of standing for each subject The averages and standard deviations for each mode are shown also.

Since all subjects essentially never showed the GRV behind the ankle (as discussed below), da was always positive. Therefore the mean distance of the GRV from the knee (dk) and hip (dh) were plotted on a scattergram for each condition, as shown in figure 3. The raw data for these plots is given in table 2.

Representative stick figures for one subject are given in figure 4, along with various graphics output of the program. This includes plots of raw data (position of knee, hip, and shoulder, force plate F_z and M_x) and calculated data (dh, dk, da calculated from force plate data, da calculated from segment positions, difference between two methods of calculating da [error], and hip, knee and ankle angles) over time. Note that when the subject is properly aligned on the force plate that da is equivalent to the y-coordinate of the GRV. To better visualize the potential synergies in joint angles, plots of joint angle versus joint angle were also prepared for various combinations of hip, knee and ankle.

Representative stick figures for all subjects are shown in figure 5 for the experimental condition of long standing. Each stick figure was selected to show one posture in the prefered mode.

In the absence of significant angular accelerations or movements of the arms, there is only a small error between the measured and computed GRV.

DISCUSSION

Differences Between Subjects: In the long term stance, 5 of the subjects spent essentially 100% of their time in a single mode

A

Strategy	AVG	sd	Subj 1	Subj 2	Subj 3	Subj 4	Subj 5	Subj 6	Subj 7	Subj 8	Subj 9	Subj 10	Subj 11	Subj 12
1 + + +	16.28	34.29	1.21	2.96	0.09	0.04	0	0	91.72	0	0.13	94.04	0	5.12
2 - + +	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
3 + - +	1.82	4.22	13.61	0	0	0	0	0	6.26	0	0.02	0	0	0
4 - - +	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
5 + + -	60.16	44.90	0.65	95.79	85.26	38.67	100	100	0	100	0.7	5.94	100	94.88
6 - + -	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
7 + - -	21.75	35.67	84.83	1.25	14.86	61.29	0	0	0.02	0	99.16	0.2	0	0
8 - - -	0.00	0.00	0.01	0	0	0	0	0	0	0	0	0	0	0

B

Strategy	AVG	STD DV	Subj 1	Subj 2	Subj		Subj 5	Subj 6	Subj 7	Subj 8	Subj 9	Subj 10	Subj 11	Subj 12
1 + + +	8.33	27.64	0	0	0	0	0	0	100	0	0	0	0	0
2 - + +	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
3 + - +	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
4 - - +	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
5 + + -	83.33	37.27	0	99.93	100	100	100	100	0	100	100	100	100	100
6 - + -	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
7 + - -	8.34	27.64	100	0.07	0	0	0	0	0	0	0	0	0	0
8 - - -	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0

C

Strategy	AVG	STD DV	Subj 1	Subj 2	Subj 3	Subj 4	Subj 5	Subj 6	Subj 7	Subj 8	Subj 9	Subj 10	Subj 11	Subj 12
1 + + +	7.82	16.95	6.81	0	0	1.89	16.47	0	61.88	0.46	0	6.17	0	0.59
2 - + +	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
3 + - +	3.33	8.13	11.98	0	0	0	0	0	27.99	0	0	0	0	0
4 - - +	0.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
5 + + -	65.19	32.09	0	67.38	96.51	62.3	79.49	100	1.76	99.54	69.92	68.29	84.64	53.39
6 - + -	0.34	1.12	0	0	0	0	4.04	0	0	0	0	0	0	0
7 + - -	20.74	18.90	58.72	32.62	4.49	34.7	0	0	8.4	0	30.08	25.63	9.64	44.6
8 - - -	2.59	6.29	22.79	0	0	1.11	0	0	0	0	0	0	5.73	1.43

1: Strategy Matrices for each experimental condition for each subject indicates percent of time spent in mode. Average and Standard deviations for all subjects ı at left. A: Standing 22 min 40 sec, B: Standing 80 C: Slow sway at ankles 80 sec.

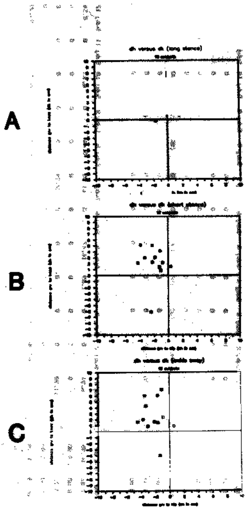


FIGURE 3: Scattergrams of dh versus dk for the three experimental conditions. Each point represents the mean values of a single subject. See table 2 for raw data. A: Standing 22 min 40 sec, B: Standing 80 sec, C: Slow sway at ankles 80 sec.

A

	AVG	STD DV	Subj 1	Subj 2	Subj 3	Subj 4	Subj 5	Subj 6	Subj 7	Subj 8	Subj 9	Subj 10	Subj 11	Subj 12
mean dh	-1.82	1.82	-1.5	-0.64	-3.05	-1.62	-2.91	-2.87	1.67	-3.14	-3.43	0.89	-4.78	-0.45
sd dh	0.60	0.28	1.21	0.38	0.46	0.64	0.36	1.01	0.71	0.7	0.57	0.62	0.35	0.27
absval mean	2.28	1.26	1.5	0.64	3.05	1.62	2.91	2.87	1.67	3.14	3.43	0.89	4.78	0.45
mean dk	1.26	2.57	-5	1.08	0.82	-0.19	3.54	4.67	0.77	3.71	-1.84	2.9	2.07	2.68
sd dk	0.79	0.38	1.62	0.41	0.8	0.76	0.44	0.76	0.74	0.91	1.18	0.79	0.37	0.73
absval mean	2.43	1.51	5	1.08	0.82	0.19	3.54	4.67	0.77	3.71	1.84	2.9	2.07	2.68
mean da	5.09	1.03	5.38	5.52	4.73	7.15	3.66	4.58	6.15	3.47	4.5	5.21	4.46	6.24
sd da	0.92	0.39	1.84	0.57	0.71	1.05	0.69	0.98	0.91	0.77	0.87	1.08	0.4	0.67
absval mean	5.09	1.03	5.38	5.52	4.73	7.15	3.66	4.58	6.15	3.47	4.5	5.21	4.46	6.24

B

	AVG	STD DV	Subj 1	Subj 2	Subj 3	Subj 4	Subj 5	Subj 6	Subj 7	Subj 8	Subj 9	Subj 10	Subj 11	Subj 12
mean dh	-1.90	1.27	-2.48	-1.02	-1.01	-1.24	-2.2	-3.88	0.37	-1.13	-4.2	-0.78	-3.25	-2.19
sd dh	0.16	0.05	0.28	0.14	0.1	0.17	0.18	0.21	0.1	0.18	0.19	0.15	0.12	0.13
absval mean	2.04	1.17	2.48	1.02	1.01	1.24	2.2	3.88	0.37	1.13	4.2	0.78	3.25	2.19
mean dk	2.08	2.79	-6.11	0.85	3.08	1.43	5.05	5.14	1.84	4.14	2.1	2.16	2.99	2.24
sd dk	0.32	0.11	0.44	0.25	0.29	0.25	0.23	0.51	0.25	0.51	0.3	0.23	0.24	0.14
absval mean	3.07	1.61	6.11	0.85	3.08	1.43	5.05	5.14	1.84	4.14	2.1	2.16	2.99	2.24
mean da	6.10	1.38	3.64	5.3	7.13	6.27	6.01	6.99	8.99	4.84	6.26	5.21	5.6	7.95
sd da	0.49	0.17	0.48	0.43	0.37	0.44	0.33	0.91	0.38	0.75	0.44	0.34	0.38	0.58
absval mean	6.10	1.38	3.64	5.3	7.13	6.27	6.01	6.99	8.99	4.84	6.26	5.21	5.6	7.95

C

	AVG	STD DV	Subj 1	Subj 2	Subj 3	Subj 4	Subj 5	Subj 6	Subj 7	Subj 8	Subj 9	Subj 10	Subj 11	Subj 12
mean dh	-2.17	1.39	-1.38	-1.63	-3.7	-2.09	-1.66	-3.47	0.59	-1.08	-4.45	-0.87	-3.31	-3.04
sd dh	0.70	0.36	1.4	0.59	0.4	1.02	1.44	0.54	0.47	0.47	0.61	0.55	0.7	1.21
absval mean	2.27	1.22	1.38	1.63	3.7	2.09	1.66	3.47	0.59	1.08	4.45	0.87	3.31	3.04
mean dk	2.53	2.09	-4.08	1.47	2	1.63	6.08	6.04	0.9	7.08	1.6	2.39	4.3	0.86
sd dk	2.49	0.61	2.62	2.13	1.18	2.9	3.19	1.8	2.99	2.29	2.37	2.49	3.46	3.13
absval mean	3.20	2.18	4.08	1.47	2	1.63	6.08	6.04	0.9	7.08	1.6	2.39	4.3	0.86
mean da	6.08	1.23	3.53	6.85	7.63	7.08	6.60	7.79	7.80	7.73	5.66	6.77	8.32	6.68
sd da	3.91	0.80	3.58	3.43	2.43	4.59	4.09	2.88	4.1	3.83	3.32	4.13	5.26	4.52
absval mean	6.08	1.23	3.53	6.85	7.63	7.08	6.60	7.79	7.80	7.73	5.66	6.77	8.32	6.68

TABLE 2: Mean distances between GRV and joint centers of rotation for each subject. Average and standard deviation for all subjects shown at left. This is raw data for the plots shown in figure 3. A: Standing 22 min 40 sec; B: Standing 80 sec; C: Slow sway at ankles 80 sec.

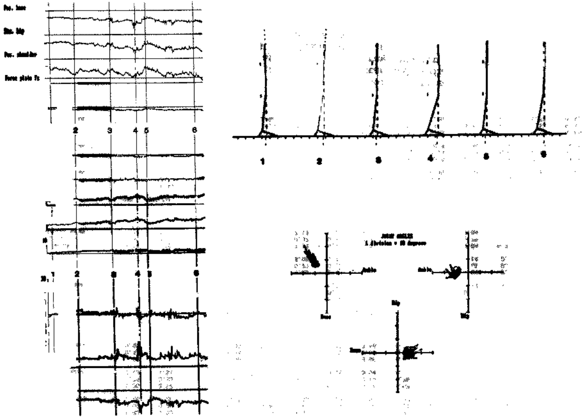


FIGURE 4: Typical data record for long term standing showing raw and calculated data versus time. Six stick figure representations shown for selected times. Angle/angle plots also shown.

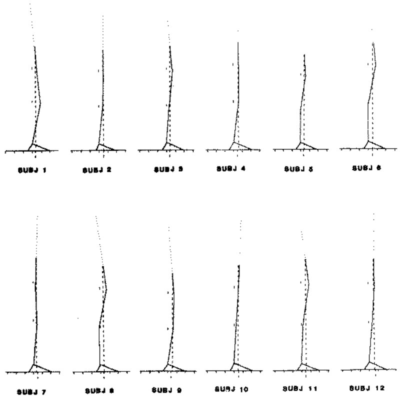


FIGURE 5: Typical stick figure representations for all subjects during long period of stance. Dashed line above ground is GRV calculated from segment positions. Dashed line below ground is GRV measured by force plate. Dotted line is extension of trunk beyond center of mass. Two vertical reference marks appear above the ankle at levels of knee and hip.

of stance. Of subjects who spent more than 2% of their time in more than one posture, five of the subjects switched postural modes at the hip and three switched postural modes at the knee. These differences in the subtleties of biomechanical configuration may accout for the wide discrepancies reported for which muscles are active during quiet stance in man. In the other two experimental conditions, subjects displayed similar results. Even during slow sway at the ankles, some subjects exhibited only one mode of standing.

Selection of Modes of Stance: One of the striking features of the data is that one GRV almost never passed behind the ankle. This has been previously noted by a number of investigators [22], and is due to the length imbalance of the foot relative to the ankle. This immediately allows four of the standing modes to be classified as not typically used and implies that the soleus must always be active. Of the three values da, dk, and dh, da was always the the largest. Of the four remaining modes, one is clearly favored, two are used infrequently, and one is essentially never used. One may speculate on the possibility that this reduction in "degrees of freedom", so to speak, may make for a simplification of the requirements of the CNS for postural regulation during quiet stance. The preferred posture (++-) also appears to be the posture requiring minimal activation of extensor musculature; only the soleus (which is a very fatigue resistant muscle) need be active. The posture which is essentially never seen (+-+) is a stooping posture, and theoretically requires maximal activation of extensors. As noted above, the quantities dk and dh were typically smaller than da. This appeared to be due to the anatomical substrate and the constraints at the hip and knee. Even subjects that clearly preferred a single mode did not have values of dk and dh that approached the value of da, except when dk was influenced by knee hyperextension (3 subjects).

Relevance to FES: It is interesting to speculate on the relevance of these data to clinical attempts at restoring standing in paralyzed individuals. For example, transient periods of standing can be obtained in a select population of mid-thoracic paraplegic individuals using bilateral electrical stimulation of the quadriceps to stabilize the knees [18,19]. This simplest scheme may not be entirely satisfactory because of fatigue of the quadriceps when undergoing constant stimulation. The notion of posture switching has been introduced as a potential solution to the problem of fatigue, which would allow the quadriceps periods of rest [23,24]. It should be noted that another possible solution to the fatigue problem would be asynchronous stimulation of different parts of the muscle subject to fatigue [25]. One of the interesting interpretations of the data of the present study is that postural switching in the sagittal plane may not be the only way to combat fatigue, since it is not frequently observed in normal subjects. New preliminary data (not part of this report) and other findings concerning EMG in right and left legs during stance [26] may suggest that posture switching may also be fruitfully pursued in the lateral plane. Further studies must compare the biomechanical configuration with actual muscle activation as measured by EMG in neurologically intact subjects.

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