

Speed–Accuracy Trade-Off in Voluntary Postural Movements

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We investigated the speed and accuracy of fast voluntary movements performed by the whole body during standing. Adults stood on a force plate and performed rhythmic postural movements generating fore and back displacements of the center of pressure (shown as online visual feedback). We observed that for the same target distance, movement time increased with the ratio between target distance and target width, as predicted by Fitts'–type relationships. For different target distances, however, the linear regressions had different slopes. Instead, a single linear relation was observed for the effective target width versus mean movement speed. We discuss this finding as a result of the pronounced inherent variability of the postural control system and when such a source of variability is considered, the observed relationship can be explained. The results reveal that the accuracy of fast voluntary postural movements is deteriorated by the variability due to sway during standing.

Key Words: posture, balance, center of pressure, human movement, motor control, Fitts' law

The control of voluntary reaching movements to a target and the control of balance during standing are two fundamental functions of our nervous system, each of which have been intensely investigated for decades. These two functions, however, have been studied by different groups in the motor control literature with almost no overlap. At a closer look, though, these two actions are not as distinct as they appear. Quite frequently in our daily activities, we perform very accurate “aiming” movements with our whole body while standing. Examples of accurate postural displacement include leaning forward in an upright posture to reach for something while avoiding falling, transferring from a seated to a standing position, and during stair walking. In this context, clinical tests involving rapid aiming movements from one target to another with a global variable representing body sway (body center of gravity or center of pressure) have been used in the evaluation and rehabilitation of the control of balance (Hageman et al., 1995; Hamman et al., 1995; Nichols, 1997). It is important to note that a failure to perform accurate and fast movements

might lead to inadequate postural responses which could ultimately lead to a fall, a serious problem in the elderly population (Rogers et al., 2003).

Since the early experiments of Woodworth (1899), many studies have elaborated and detailed the basic finding that accuracy and speed of movement performed with the hand or any other body segment are related. The trade-off between speed and accuracy for aiming movements has produced a very robust result in a large number of studies: faster movements are less accurate and higher accuracy is achieved at lower speeds. Fitts' law expresses the most well known relation of this trade-off for spatially constrained movements (Fitts, 1954):

$$MT = a + b \cdot \log_2(2D/W)$$

where MT is the movement time, D the target distance, W the target width, a and b are empirical constants, and where $\log_2(2D/W)$ is termed the Fitts' index of difficulty (ID). Over the years, different mathematical formulations have been proposed. The most accepted today seem to be functions of the type (Fitts, 1954; Welford et al., 1969; Crossman & Goodeve, 1983; Meyer et al., 1988; Gutman & Gottlieb, 1992; Plamondon & Alimi, 1997):

$$MT = a + b \cdot (D/W)^p$$

where $0 < p < 1$. In some of these formulations, $W/2$ is used instead of W and a constant can be added to the D/W term. The logarithmic function, as in Fitts' law, is a first order approximation of this type of power function and Fitts' law is equivalent to a power function when p tends to zero.

Previous studies on voluntary movements of the whole body during standing have mainly focused on amplitude and time constraints, such as a given sway amplitude or frequency (Alexandrov et al., 2001; Schieppati et al., 2002; Buchanan & Horak, 2003; Latash et al., 2003). The only study that explicitly addressed movement accuracy, to our knowledge, was the study by Danion, Duarte, and Grosjean (1999). Standing on a force plate, participants were asked to perform cyclical movements between two targets with visual feedback of the center of pressure (COP) location, which was shown on a screen together with the targets. Results showed that for each target distance, movement time indeed showed a trade-off with the target width, as expressed in Fitts' law (Fitts, 1954). Danion et al., (1999), however, also observed a violation of Fitts' law in their experiment: the movement time, performed for conditions with different target distances but with the same ratio between target distance and target width (the same index of difficulty), increased with a decrease in the target distance. Danion et al. (1999) conjectured that this violation might be related to the COP variability present during standing. Different from movement tasks performed with other body segments, as, for instance, the hand, posture shows a nonnegligible inherent variability (Duarte & Zatsiorsky, 2002).

The effect of variability that is independent of the movement itself on the speed-accuracy trade-off can be more directly examined with the relation between the mean movement speed and effective target width. Effective target width, W_e , has been defined as the actual dispersion of the endpoint over repeated performances replacing the target width as the measure for accuracy. Mean movement speed, S , is the ratio between the target distance and movement time, D/MT . Hence, the

other formulation for the speed–accuracy trade-off is (Schmidt et al., 1979; Meyer et al., 1982):

$$W_e = a + b \cdot S$$

where a and b are empirical positive constants. The slope b expresses how much a change in movement speed affects movement variability, while the intercept a expresses the variability at zero speed. Therefore, the intercept a is a measure of the variability that is independent of the movement speed. As postural sway exists during standing, i.e., now interpreted as variability at zero speed, this relation might be more appropriate than Fitts' law to investigate if and how postural sway affects the speed–accuracy trade-off.

In this article, we explore the observed behavior in the speed–accuracy trade-off during standing as the result of postural sway. We reproduced the experiment of Danion et al. (1999) by increasing the number of conditions, and further performed additional data analysis testing different speed–accuracy trade-off relations. In addition, we derived a model that can account for the observed phenomena by explicitly considering the inherent variability of the postural control system.

Methods

Eleven adults (seven women and four men) volunteered for this study. The participants' mean age, height, and mass ($\pm SD$) were: 28 ± 6 years, 169 ± 5 cm, and 65 ± 10 kg. All participants were healthy with no prior physical or mental illnesses and they had normal or corrected to normal vision. Before their participation, they signed an informed consent form approved by the local ethics committee of the University of São Paulo.

Experimental Setup

Participants stood on a force plate (model OR6-WP-1000, AMTI, Watertown, MA) where the instantaneous COP position in the anterior–posterior direction was measured and shown as online feedback on a computer monitor. The cursor was a yellow dot moving on a black background. The COP displacement in the anterior–posterior direction resulted in a vertical movement of the cursor (see Figure 1). The lateral displacement of the COP was suppressed in the display to avoid distraction. Two target zones were shown, delimited by two red lines that were perpendicular to the direction of the vertical movement. The monitor was located 1 m in front of the participant at an adjustable height, so that the center of the monitor was aligned with the participant's eye height. The visual feedback of the COP position and the targets were programmed in a custom-written code written in LabVIEW software, that acquired the force plate signals at a sampling frequency of 100 Hz (LabVIEW 6.1, National Instruments Corp., Austin, TX). The data acquisition was performed using a standard personal computer with a 16-bit A/D board (model PCI 6431, National Instruments).

Task and Experimental Design

The participants' tasks consisted of performing oscillatory body movements for 30 s as fast and as accurately as possible, such that they generated up and down

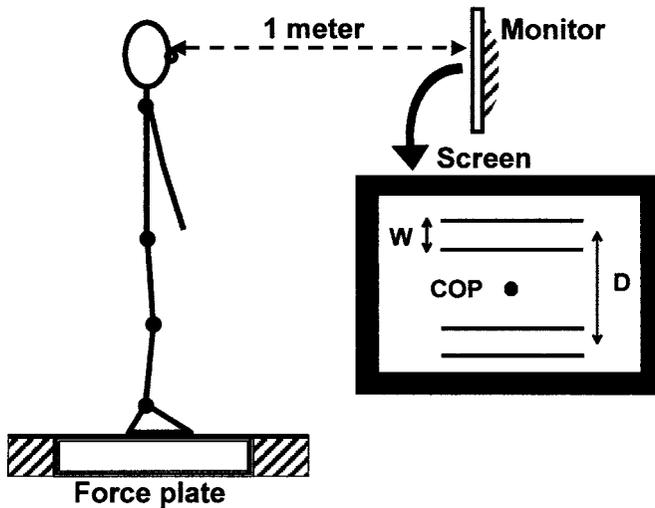


Figure 1 — Illustration of the experimental setup.

displacements of the cursor (COP position) between the two targets. They were allowed to voluntarily oscillate in the anterior–posterior direction as they wished with no major restriction except that they were told not to move their feet and to keep their arms along their trunk. Note that using this type of feedback makes COP the main performance variable. The center positions of the target zones were determined for each individual in relation to the COP's neutral position and the limits of stability. To that end, prior to the actual experiment, the participants were asked to stand in a comfortable position with their feet approximately one shoulder width apart. Then, the COP's neutral position was determined as the average COP position during quiet stance with eyes open in a 30 s trial (no COP feedback). Subsequently, the limits of stability were determined as follows: Participants were asked to slowly lean forward and backward as far as possible while keeping both feet completely on the ground. The maximal positions of the COP in both forward and backward directions were considered as the limits of stability in the anterior and posterior directions. Finally, the proportion between these limits of stability and the COP's neutral position was used to place the virtual targets on the screen. For example, if a participant could lean twice as far forward as backward, then, in relation to the COP neutral position, the center of the forward target was located twice as distant from the neutral position as the center of the backward target (see Figure 2 for an example of targets and neutral positions).

Five target distances, D , (3, 4.5, 6, 9, and 12 cm) combined with seven of Fitts' indices of difficulty, $ID = \log_2(2D/W)$, (1.4, 1.7, 2.0, 2.3, 2.6, 2.9, and 3.2) were prescribed. This produced a total of 35 different task conditions. The ratios between the different target distances and target widths, D/W , were 1.32, 1.62, 2.00, 2.46, 3.03, 3.73, and 4.59. The target widths varied from 0.7 to 9.1 cm. These target distances and ID s were chosen based on the feasible range of tasks that the participants could successfully perform with no more than 10% error. An error was

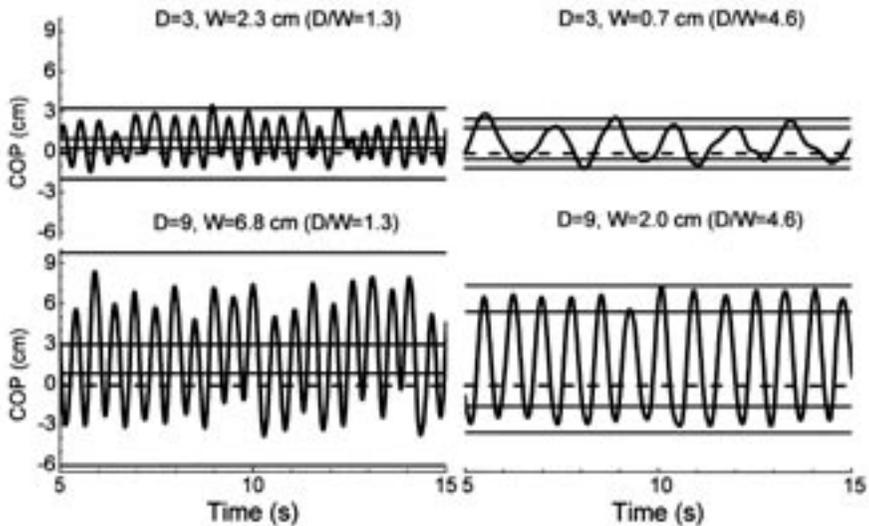


Figure 2 — Representative 10 s of the COP displacement time-series for four different target distance (D) and ratio between target distance and target width (D/W) combinations: $D = 3$ cm, $W = 2.3$ cm ($D/W = 1.3$); $D = 9$ cm, $W = 6.8$ cm ($D/W = 1.3$); $D = 3$ cm, $W = 0.7$ cm ($D/W = 4.6$); and $D = 9$ cm, $W = 2.0$ cm ($D/W = 4.6$). The two targets are shown as zones between horizontal lines and the participant's neutral position is represented as a dashed line.

defined as an over- or undershoot of the target, and the percentage of errors was computed for each 30-s trial.

After the targets were specified for each participant, he or she performed a training session with varied distances and widths. The participants were asked to perform oscillatory movements in such a way that they generated forward and backward displacements of the cursor between the two targets as quickly and accurately as possible. They were also encouraged to move the cursor from center to center of the targets. After the participant felt comfortable with the task, 35 trials of 30 s duration each were performed in a randomized sequence. A trial containing more than 10% errors was rejected and repeated at the end of the experiment. Between trials, participants could rest or walk around, as they preferred, but fatigue was never an issue. The participant's foot position was marked on the force plate and reproduced across trials.

Data Analysis

Only the COP displacements in the anterior–posterior direction were analyzed. The first 10 s of the 30 s COP time series were considered as an adaptation period and were discarded from the data analysis after the filtering process. Subsequently, the COP data were low-pass filtered at 10 Hz with a fourth-order, zero-lag Butterworth filter.

To calculate movement time, the peaks and valleys of the oscillatory COP signal were detected from the time series (see Figure 2 for an example of time series). The forward movements (half cycle) were defined by consecutive valley and peak points, and the backward movements were defined by consecutive peak and valley points. The mean amplitude of the movements in a trial determined the effective target distance. A full-cycle, i.e., forward and backward displacement of the COP, was defined by the trajectories between two consecutive valleys. When necessary, the means and standard deviations for the cycles were computed and normalized in time to vary between 0 to 100%. The movement time was computed as the time of each forward or backward movement. The forward and backward movement times were averaged across each trial to calculate movement time without distinction as to direction.

For positioning tasks, the pointing variability is evident in the dispersion of the pointing which is usually estimated as proportional to the standard deviation of these points, the so-called effective target width. For the cyclical performance of an aiming task, it is the dispersion measured at the inflection points. The effective target width was estimated as the width containing 95% of the COP turning points. From statistics, the interval of approximately ± 2 standard deviations (a total of $4 \cdot SD$) contains about 95% of the data in a population with normal distribution. Hence, the effective target width was calculated as four times the standard deviation of the effective distances during the trial. This procedure was originally proposed by Welford and colleagues (Welford et al., 1969). Mean movement speed, S , was calculated as the ratio between mean effective distance, D_e , and mean movement time, MT : $S = D_e / MT$. The velocity and acceleration of the COP time series were calculated by direct differentiation of the COP signal and were low-pass filtered at 10 Hz with a fourth-order, zero-lag Butterworth filter.

Repeated measure ANOVAs were performed to test the effects of the seven ratios between target distance and target width (ID or D/W) and the five target distances on the dependent variable movement time. When necessary, linear regressions were performed by the method of least squares, and the correlation coefficient was used to indicate the goodness of fit. Only the significant interactions among different effects will be reported. An alpha level of 0.05 was used for all statistical tests, which were performed using SPSS version 10.0 software (SPSS, Inc., Chicago, IL).

Results

The average limit of stability of the 11 participants measured between maximal forward and backward COP excursion in the anterior–posterior direction was 18 ± 2 cm, with $65 \pm 8\%$ of the limit of stability in the forward direction and $35 \pm 8\%$ in the backward direction when measured from the neutral position. Figure 2 shows four typical time series of one participant for four different targets. The targets (solid horizontal lines) were positioned proportionally to the limits of stability of each participant, resulting in an asymmetrical positioning in relation to the neutral position (dashed lines in Figure 2). Participants were instructed to perform the movement as quickly and accurately as possible. According to a Fitts'–type relationship, movement time should be constant for the same index of difficulty.

This was only the case, however, for the lowest ratio between the target distance and target width, as shown in the two trials in the left column of Figure 2. In trials with the highest ratio between the target distance and target width, illustrated in the right column of Figure 2, the movement time differed considerably. Under the same ratio between the target distance and target width, the condition with the smallest target distance produced much slower movements than the trial with the greater target distance (right column of Figure 2).

Participants successfully performed all trials with less than 10% error, with the exception of the trials with a 3-cm distance and an ID of 2.9 ($D/W = 3.1$) and 3.2 ($D/W = 4.5$). In these conditions participants had average error rates of 10–15%. The conditions with the large target distances were easier and participants could have achieved even higher D/W ratios, which was evidently not the case for the small target distances.

Figure 3 shows plots of the movement time averaged across participants versus ID and versus the ratio between the target distance and target width. The different symbols differentiate between the different target distances, and the regressions were performed for each target distance separately. The data were fitted by Fitts' law (Fitts, 1954): $MT = a + b \cdot \log_2(2D/W)$ and by the linear equation: $MT = a + b \cdot (D/W)$. In the present study, the ratio between the target distance and target width is restricted from $D/W = 1.3$, where the targets could be clearly distinguished, and to $D/W = 4.6$, where beyond that the task was impossible to complete. Within this range, the two former equations present similar behavior. As a result, the fits by these two equations were similar: all regressions were statistically significant (all r values $> .92$ and all p values $< .005$). It will be easier, however, to mathematically handle the linear equation when we extend our analysis. For this reason, the following results are presented only for the simplest linear relation: $MT = a + b D/W$. The shortest movement times were achieved in the conditions with the lowest ratio between the target distance and target width and were the same for all target distances. The overall average movement time for the lowest ratio between the target distance and target width was 328 ± 34 ms. The longest movement time was achieved in trials with the smallest target distance and the highest ratio between the target distance and target width. It was, on average, 889 ± 105 ms.

A 5 (target width) \times 7 (index of difficulty or ratio between the target distance and target width) ANOVA statistically tested the pattern of results in panel B of Figure 3. Movement time increased with increases in the ratio between the target distance and target width [$F(6, 60) = 23.7, p < .0001$] and with decreases in the target distance [$F(4, 40) = 19.6; p < .0001$]. For each target distance, movement time showed positive linear dependencies on the ratio between the target distance and target width. We also observed an interaction between the ratio between the target distance and target width and target distance [$F(24, 240) = 3.5, p < .0001$], consistent with the different slopes of the linear regressions.

When movement time is plotted against the ratio between the effective target distance and the effective target width, representing the actual performance of the participants, a qualitatively similar pattern is observed. As Figure 4 shows, however, the separation of the different regression lines is even more pronounced than in the relation between movement time and the ratio between target distance

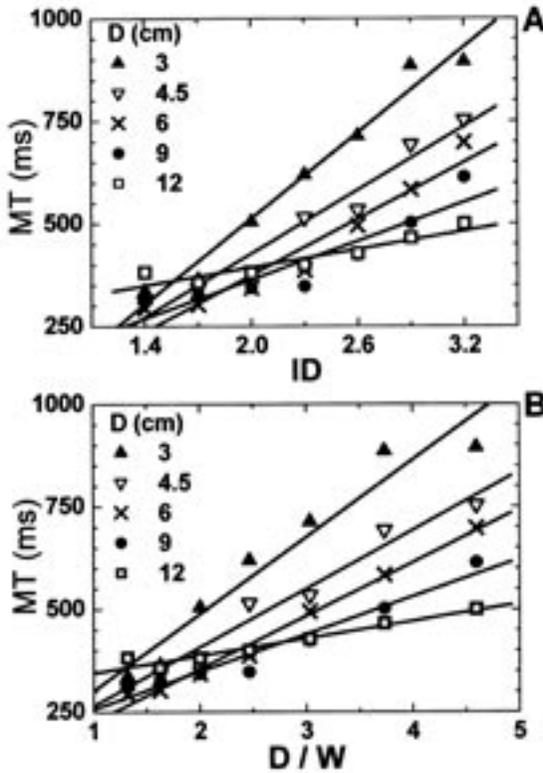


Figure 3 — (A) Mean COP movement time (*MT*) across participants versus the index of difficulty ($ID = \log_2(2D/W)$) and (B) versus the ratio between target distance and target width (D/W) for the five target distances (D). The straight lines represent the best fits by least squares.

and target width in Figure 3. As observed previously, for each distance, movement time showed a linear dependence on the ratio between the effective target distance (all r values $> .88$ and all p values $< .05$) and the effective target width and this dependence had different slopes for each target distance. The participants slightly overshoot the target distances by about 5%: the effective distances were, on average, 3.2 ± 0.1 ; 4.8 ± 0.2 ; 6.4 ± 0.2 ; 9.4 ± 0.3 ; and 12.2 ± 0.2 cm (for the prescribed distances 3; 4.5; 6; 9; and 12 cm, respectively). The effective widths, however, were significantly dependent on the target distances. The participants did not perform with the same ratio between the effective target distance and the effective target width for different target distances: the lower the effective target distance, the lower the ratio between the effective target distance and the effective target width values that were achieved. Figure 4 shows that the highest ratio between the effective target distance and the effective target width that participants could achieve on the 3-cm target distance was markedly lower than the lowest ratio

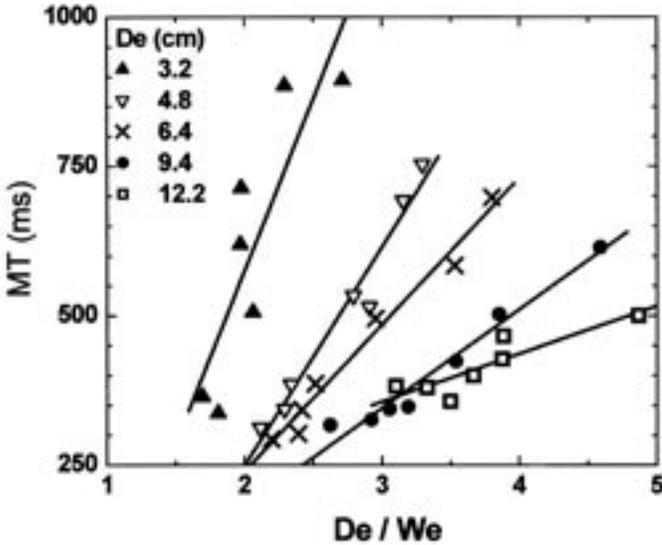


Figure 4 — Mean COP movement time (*MT*) versus the ratio between effective distance and effective width (D_e/W_e) for the five effective target distances (D_e) across participants. The straight lines represent the best fits by least squares.

between the effective target distance and the effective target width performed on the 12-cm target distance. This indicates that the accuracy the participants could achieve was dependent on the target distance.

Figure 5 shows the effective target distance, W_e , versus the mean movement speed, S , for all effective target distances and widths. The effective target distance showed a significant positive linear dependence on S : W_e [cm] = $1.01 + 0.082 \cdot S$ [cm/s], $r = .97$, $p < .0001$. Although the data for different effective target distances had different ranges of speed, they all fitted in the same linear relationship. About 94% of the variance in the effective target distance is explained by movement speed across all effective target distances. In the former linear equation, substituting S by D_e/MT and rearranging the terms, MT is given by the single equation: MT [ms] = $82 \cdot D_e / (W_e - 1.01)$ [cm]. This single equation successfully fits the data for each of the five different effective target distances, with a median value for the correlation coefficients of .95, ranging from .81 to .96 (all p values $< .05$).

Discussion

In the experiment described, healthy adults stood on a force plate and performed oscillatory body movements as quickly and accurately as possible to generate forward and backward displacements of their COP position between two targets. We observed that for the same target distance, movement time increased with the index of difficulty or the ratio between the target distance and target width as predicted by a Fitts'-type relationship. For different target distances, however, different slopes

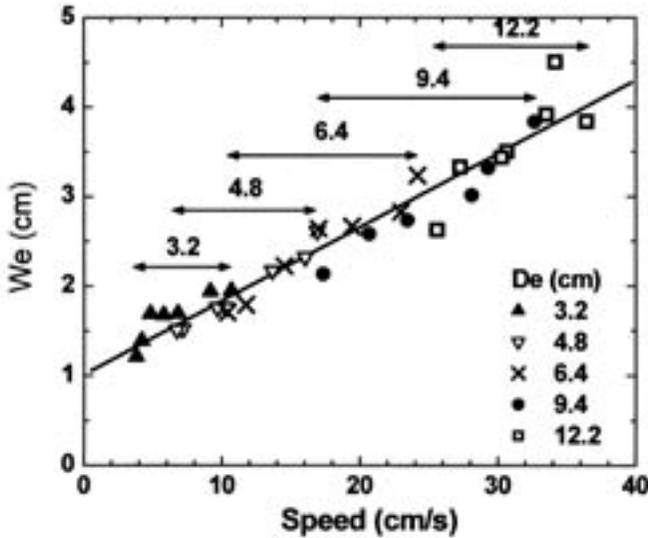


Figure 5 — Mean effective width (W_e) versus mean movement speed for the effective target distances (D_e) across participants. The straight line represents the best fit by least squares. The arrows indicate the range of speed that the data for different target distances span.

were obtained. This latter finding violates Fitts’-type relationships where only the index of difficulty, regardless of its composition, should determine movement time. The same results were already reported in an earlier study with fewer experimental conditions (Danion et al., 1999). When movement time was plotted versus the ratio between the effective target distance and effective target width, representing the actual performance of the participants, we observed the same violation. The effect of target distance, however, was even more pronounced and the participants did not perform with the same ratio between the effective target distance and the effective target width for different distances. The lower the effective target distance, the lower were the values of the ratio between the effective target distance and the effective target width.

Surprisingly, when the effective target width was plotted against mean movement speed, a single linear relation was observed across all target distances and widths. Such a linear relationship has typically been observed for temporally constrained experiments, where movement time and target distance were manipulated (Schmidt et al., 1979; Meyer et al., 1982; Wright & Meyer, 1983) but also where movements were spatially constrained (Meyer et al., 1988). Importantly, these regressions have a nonzero intercept that must be attributed to noise sources that are not directly dependent on movement speed. In the present task, there is a clear source of such noise: the irreducible sway during seemingly quiet standing. To account for these findings, we have developed a model that suggests a quantitative interpretation of this result.

A Model for the Speed–Accuracy Trade-off of Voluntary Movements During Standing

We hypothesize that the total variability during voluntary postural movements is a sum of two components: variability related to movement speed, termed the dynamic component, and variability related to postural sway, termed the quasi-static component. The dynamic component of the variability has been frequently discussed in force production as signal-dependent noise, where higher levels of forces are typically associated with more variability. This variability has been attributed to neuromotor noise in the peripheral system (Schmidt et al., 1979; Meyer et al., 1988), to dispersion in setting the control parameters (Gutman & Gottlieb, 1992), or to the variability of motor-neuronal firing (Harris & Wolpert, 1998). In modeling accounts of fast voluntary movements, the variability at the performance level caused by the dynamic component is represented by a measure of the movement dispersion (usually related to the standard deviation of the movement endpoint), W_d , that is directly proportional to movement speed (Schmidt et al., 1979; Meyer et al., 1982): $W_d = k \cdot S$, where k is a positive constant, and S is the movement speed.

The variability related to postural sway during standing, the quasi-static component, is evidenced in the observation that, while standing, humans do not stay motionless and the COP location varies over time. Despite the large number of studies on postural control, an exact understanding of the sway during quiet standing is still lacking. Theoretical interpretations for this observation range from viewing it as the output of a control process of the stabilization of an unstable system (Collins & De Luca, 1993; Jacono et al., 2004; Peterka & Loughlin, 2004) to a spontaneous active exploratory process (Riley et al., 1997). It also remains unclear how postural sway affects the COP variability of voluntary COP shifts during standing. To our knowledge, this question has been investigated in only one study (Latash et al., 2003). This study quantified the COP variability during voluntary oscillatory COP shifts between two target lines (there was no accuracy constraint) for different imposed frequencies of oscillation. A method was developed that decomposes the variability related to postural sway by applying filters in both the time and frequency domains based on the characteristics of movement and postural sway. It was shown that the variability related to postural sway was approximately constant (about 1 cm) across the different frequencies of oscillation.

Based on this result, we will consider the quasi-static component of variability as constant across different movement speeds. At the performance level, this variability is manifested as a constant dispersion or width, W_{qs} : $W_{qs} = W_o$. As a direct consequence of these assumptions, the underlying random noise processes responsible for the dynamic and the quasi-static components of variability are independent.

The total variability, i.e., the total effective target width (W_e), is the square root of the total variance which is defined as the sum of the variances of the two independent random processes (Papoulis, 1991):

$$W_e^2 = W_d^2 + W_{qs}^2 = (k \cdot S)^2 + W_o^2$$

$$W_e = \sqrt{(k \cdot S)^2 + W_o^2}$$

The two parameters of this equation are k , the weight of the dynamic component of variability, and W_0 , the quasi-static component of variability. Given data of W_e and movement speed, S , the equation can be fitted using a nonlinear least squares Levenberg-Marquardt algorithm. Figure 6 shows the curvilinear fit of the mean W_e versus the mean S across participants with this equation. The fitted equation is: $W_e = ((0.106 \cdot S)^2 + 1.45^2)^{1/2}$, $r = .97$. About 94% of the variance in effective target width is explained by the variance in mean movement speed. The parameter W_0 (1.45 cm) is the intercept, i.e., the amount of variability at zero speed. Its weight on the former equation is greater at low movement speeds and it is responsible for the nonlinearity of the equation.

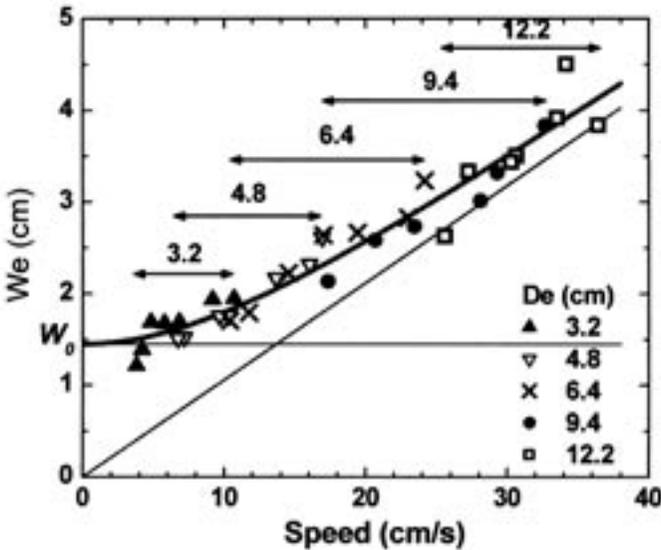


Figure 6 — Mean effective width (W_e) versus mean movement speed (S) for the effective target distances (D_e) across participants. The arrows indicate the range of speed that the data for different target distances span. The curved thick line represents the best fit with the function for the total variability ($W_e = ((k \cdot S)^2 + W_0^2)^{1/2}$). The inclined thin line represents the dynamic component of the variability ($k \cdot S$) and the horizontal thin line represents the quasi-static component of the variability (W_0).

Substituting the mean movement speed, S , by D_e/MT in Eq. 1 and rearranging the terms, movement time, MT , is then expressed as:

$$MT = \sqrt{\frac{(k \cdot D_e)^2}{W_e^2 - W_0^2}}$$

This expression shows that the quasi-static source of variability, W_0 , effectively diminishes the target width that the participant can achieve for a given speed

without error. As W_e decreases, the effect of W_0 on the $(W_e^2 - W_0^2)$ term increases, making the slope of the function MT versus D_e/W_e steeper, consistent with what is observed in Figure 4. The fact that the total variability according to the previous model is approximately constant for very slow speeds (see Figure 6) is consistent with how the participants behaved. Participants often reported that reducing movement speed did not decrease the variability for the most difficult tasks. It should be noted that this model is valid only for $W_e > W_0$, i.e., for a task where the actual movement dispersion that is allowed is greater than the inherent variability of the participant.

When Eq. 2 with the previously adjusted values of the parameters k and W_0 , $MT = ((0.106 \cdot D_e)^2 / (W_e^2 - 1.45^2))^{1/2}$, was used to separately fit the data of each of the five effective target distances, the median value of the five correlation coefficients equaled .96, ranging from .82 to .98 (all p values $< .05$). Notice that in this modeling only one equation with the same two parameters was used to perform five different fits. The results show that only two parameters sufficed to fit all data. This is in contrast to the 10 parameters that were necessary to fit the data of a Fitts'-type equation (two parameters for each of the five fits).

If the interpretation of the intercept as an additional constant source of variability is correct, the present model predicts that the intercept values are positively correlated with the quasi-static component of the total variability. Participants with more sway during quiet standing should have higher intercept values. To test this prediction, we correlated across participants the adjusted intercept, W_0 , with the sway path during a quiet standing trial. The sway path (also termed mean COP speed) is calculated as the total length of the COP displacement in the anterior-posterior direction divided by the duration of the trial. The sway path reveals the accumulated COP excursion per second and is more reliable than other measurements of the COP spatial variability during quiet standing (Baratto et al., 2002). Panel A of Figure 7 shows W_0 against the sway path of each participant. It can be seen that W_0 and the sway path are indeed positively correlated across participants ($r = .78$, $p < .005$). In contrast, Figure 7 panel B shows that there is no systematic relation between the slope of the dynamic component, k , and the COP sway path across participants ($r = .02$, $p = .95$). This latter result corroborates our initial assumption that the two variability components are independent.

Conclusion

In the present experiment, the participants seem to have used the whole body to perform multijoint movements that varied among individuals and targets. One could ask about the role of inertia and different joint strategies in explaining the observed violation. Although we did not test these hypotheses, we believe that the body mass cannot account for the observed violation. A study of the rapid oscillatory motion of the trunk, using the Fitts experimental paradigm (with the trunk angle as online visual feedback) was conducted by Kim and collaborators (Kim et al., 1996). They did not observe any indication of a possible effect of the upper body mass in splitting the MT versus ID data from the small-distance targets to the large-distance targets; a single linear regression fitted all the data well (Kim et al., 1996). In addition, in the present study we provided participants with online visual feedback of their

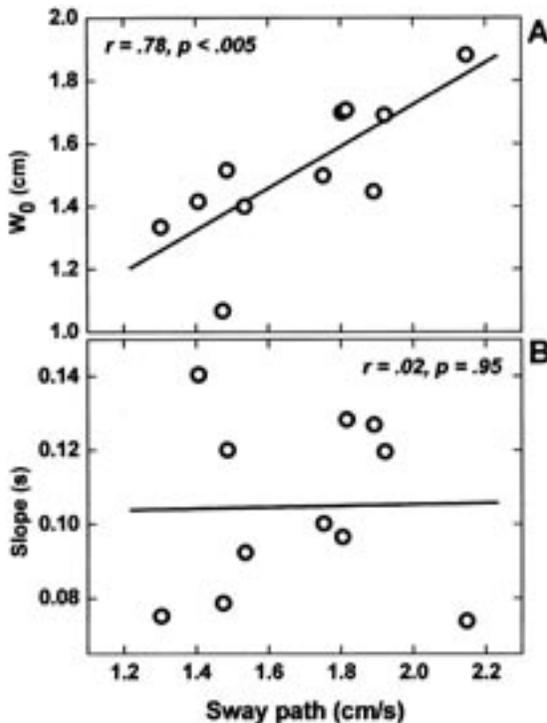


Figure 7 — (A) The quasi-static component of variability, W_0 , and (B) the slope of the dynamic component of variability, k , versus the sway path for each of the 11 participants. The straight lines represent the best fits by least squares.

COP. The COP is the point of application of the resultant of vertical forces acting on the surface of support and therefore represents the collective outcome of the activity of the postural control system and the force of gravity. The COP position is not directly related to the position of any particular segment of the body, nor is it directly related to the whole body of the participant. The COP position is different from the center of gravity position as the latter indicates the global position of the body, while the COP includes the dynamic components related to the body's acceleration. This means that it is possible to displace the COP position without considerably changing the body position. Therefore, the inertia per se does not constrain the movement of the COP. We cannot, however, completely rule out that at least part of the observed violation might be explained by inertia or by different strategies in displacing the COP, and this aspect deserves further attention.

On average, the participants studied here performed complete oscillations with frequencies ranging from 0.6 Hz to 1.5 Hz. This means that not only did the task involve multijoint movements, but also frequency-dependent multisensory information (Buchanan & Horak, 2003). In the present experiment, visual and vestibular information were probably more used at the slow frequency components

of the control of movement during standing, whereas proprioceptive information was more used at the fast frequency components (Buchanan & Horak, 2003). Even considering the different motor and sensory aspects in movement control throughout the range of frequencies of sway, it is surprising that we still observed a linear increase of movement time from the easiest (fastest) to the most difficult (slowest) task for each target amplitude we studied.

Voluntary postural movements or response to perturbations during standing have been intensely studied and employed in the clinical context to characterize posture control in humans. Most of these studies, however, have been limited to tasks with no accuracy requirements or with the accuracy not explicitly manipulated. This practice overlooks an important aspect in everyday activities. The present findings show that voluntary movements of healthy adults during standing are dependent on the accuracy requirements in a specific way. Movements of small amplitude are slower than large movements with equal relative accuracy requirements. The higher the accuracy constraint, the bigger is this difference. We interpreted this phenomenon as being caused by the inherent variability of the postural system, evident in the irreducible postural sway during standing. As a consequence, people with higher variability during standing, such as elderly persons and individuals with postural control impairments, should be more affected when performing voluntary movements during standing, particularly for movements with high accuracy demands.

Tasks involving whole body movement from one target to another have been used in the evaluation and rehabilitation of persons with postural deficits (Hageman et al., 1995; Hamman et al., 1995; Nichols, 1997). In such cases, the target distance is usually scaled to the limits of stability (LOS) of the participant being evaluated. Participants with more severe postural deficits could present shorter LOS; consequently the targets will be closer together, which might make the task more difficult, requiring a longer movement time. It could be possible, that is, that this participant presents a long movement time only because he or she had to perform a movement of small amplitude and not resulting from a postural deficit related to the control of movement during standing. Another important aspect is that the instrumental noise related to the measurement of the COP with a force plate could be nonnegligible and contribute to the component of variability independent of the movement speed. This means that the noise of the experimental apparatus might deteriorate movement performance and, if not controlled, compromise the measurement.

In sum, the present findings clarify some aspects of how voluntary movements are performed during standing by healthy adults. We found that movement performance is affected by both sources of variability, postural sway, and movement variability, and that these sources of variability seem to be uncorrelated in healthy adults. The extent to which postural sway and variability during voluntary movements are related in different balance conditions is unknown at this time and needs to be clarified in future work.

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