Exp Brain Res (2007) 180:457–467
DOI 10.1007/s00221-007-0871-x

RESEARCH ARTICLE

Effects of postural task requirements on the speed–accuracy trade-off

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Received: 14 November 2006 / Accepted: 9 January 2007 / Published online: 2 February 2007
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Abstract We investigated the speed–accuracy trade-off in a task of pointing with the big toe of the right foot by a standing person that was designed to accentuate the importance of postural adjustments. This was done to test two hypotheses: (1) movement time during foot pointing will scale linearly with ID during target width changes, but the scaling will differ across movement distances; and (2) variations in movement time will be reflected in postural preparations to foot motion. Ten healthy adults stood on the force plate and were instructed to point with the big toe of the right foot at a target (with widths varying from 2 to 10 cm) placed on the floor in front of the subject at a distance varying from 10 to 100 cm. The instruction given to the subjects was typical for Fitts' paradigm: "be as fast and as accurate as possible in your pointing movement". The results have shown that movement time during foot pointing movements scaled with both target distance (D) and target width (W), but the two dependences could not be reduced to a single function of W/D, confirming the first hypothesis. With respect to the second hypothesis, we found that changes in task parameters led to proportional variations in movement speed and indices of variability of the postural adjustments prior to leg movement initiation, confirming the second hypothesis. Both groups of observations were valid over the whole range of distances despite the switch of the movement strategy in the middle of this range. We conclude that the speed–accuracy trade-off in a task with postural adjustments originates at the level of movement planning. The different dependences of movement time on D and W may be related to spontaneous postural sway (migration of the point of application of the resultant force acting on the body of the standing person). The results may have practical implications for posture and gait rehabilitation techniques that use modifications of stepping accuracy.

Keywords Posture · Stepping · Speed–accuracy trade-off · Anticipatory postural adjustments

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Introduction

Any human motor action may be viewed as built of two components that are sometimes addressed as "focal" and "postural". For example, a quick motion of a joint of a multi-joint limb is accompanied by changes in the activity of muscles crossing other joints of the limb that are not supposed to move (Koshland et al. 1991; Latash et al. 1995). The purpose of these changes is not to produce movement but to avoid movement that would otherwise occur because of the joint coupling forces. When a standing person produces a movement that can potentially disturb the postural equilibrium, the movement is preceded by anticipatory postural adjustments (APAs)—changes in the activity of apparently postural muscles that can be seen about 100 ms prior to the movement initiation leading to early changes in mechanical variables (Belen'kii et al. 1967; Cordo and Nashner 1982; Massion 1992; Aruin and Latash 1995). APAs have been described for a variety of tasks including raising one of the legs and making a step (Rogers and Pai 1990,1995; Brunt et al. 1999, 2000; Ito et al. 2003).

Commonly, postural adjustments have been viewed as a means of generating forces and moments of force that counteract the predicted mechanical effects of the planned action on the postural task (Bouisset and Zattara 1987). As such, APA modulation with task requirements reflects processes at the level of action planning. Imagine now that variations of task requirements (such as target distance and/or target size) lead to reproducible variations of action characteristics (such as movement time). If changes in the action originate from feedback processes triggered after the action has been initiated, these changes are not expected to correlate with variations in APAs (such as shifts of the center of pressure, COP—the point of application of the resultant force acting on the body). On the other hand, if adjustments at the level of action planning are involved, APAs may be expected to scale in parallel with action characteristics.

In this study, we used this logic to explore the origins of speed–accuracy trade-off in a task that was designed to accentuate the importance of postural adjustments. Namely, we asked the subjects to point with the big toe of the right foot at targets of different sizes placed at different distances. Note that for shorter distances, such an action does not require making a step, while for longer distances it does. A quick leg motion, whether it is a pointing or a stepping motion, is preceded by APAs that are necessary to shift the body weight to the supporting leg (Brunt et al. 1991). If variations in movement time with target width and distance are reflected in variations of the postural preparation, the origin of the speed–accuracy trade-off is likely to be at the level of action planning and early stages of its preparation (Latash and Gutman 1993) but not represent a result of consecutive submovements emerging based on sensory feedback as the movement unfolds (Meyer et al. 1988b).

The task we used was similar to those that have formed the experimental foundation of the famous Fitts' law (Fitts 1954). This law describes changes in movement time (MT) when a person tries to perform a fast and accurate movement over a variety of distances and to a variety of targets. Traditionally, it has been expressed using the notion of the index of difficulty (ID), $\mathrm{ID} = \log_2(2D/W)$, where D is distance to the target and W is its width: $\mathrm{MT} = a + b \times \mathrm{ID}$, where a and b are empirical constants. Recent studies have documented violations to this relationship when the subjects are required to move rhythmically the COP or one of the leg joints between two targets (Danion et al. 1999; Duarte and Freitas 2005; Freitas et al. 2006). A single relation $\mathrm{MT} = a + b \times \mathrm{ID}$ failed to account for the data distributions suggesting that variations of the movement distance and target width could have unequal effects on MT. Based on these observations, we expected constraints associated with the control of vertical posture to lead to non-equivalent effects of variation in target width and target distance on movement time.

The present study tested two specific hypotheses: (1) movement time during foot pointing will scale linearly with ID during target width changes, but the scaling will differ across movement distances; and (2) variations in movement time will be reflected in postural preparations to foot motion.

Materials and methods

Subjects

Ten healthy adults took part as subjects in the experiments. The mean (±SD) age of the subjects was 32 ± 8 years, their mean (±SD) height was 1.71 ± 0.10 m, and their mean (±SD) body mass was 70 ± 20 kg. All participants signed the informed consent form according to the procedures approved by the Office for Research Protection of the Pennsylvania State University.

Apparatus

During the experiment, the subject stood on a force platform (OR6-5, AMTI Inc.) with the feet in parallel and separated by 10 cm and with the arms crossed over the chest. The position of the feet was marked and reproduced across trials. The force platform was used to record time patterns of three components of the force (F_x, F_y, and F_z) and three components of the moment (M_x, M_y, and M_z); x, y, and z are the anterior–posterior (AP), medio-lateral (ML), and vertical directions, respectively. These force and moment components were used to calculate the COP location in the anterior–posterior direction as $\mathrm{COP}_x = (M_y)/F_z$. The force platform data acquisition was controlled by software written in LabView 5.0 (National Instruments). A computer digitized the force platform data at 200 Hz with a 12-bit resolution by an A/D card (National Instruments). In addition, kinematics of the right side of the body was recorded using passive markers and a two-camera

ProReflex system (MCU240, Qualisys Inc.) running at 200 Hz controlled by proprietary software (QTM, Qualisys Inc.). This software was also used for digitization and reconstruction of the marker positions. The two systems were synchronized using a rectangular electrical triggering pulse to initiate the data acquisition in both systems. Passive markers were placed on the following bony landmarks of the body right side: first metatarsal head (big toe), 5 cm in the anterior–posterior direction from the tip of the toe, lateral malleolus, femoral epicondyle, greater trochanter, and acromium.

Procedures

The subjects were instructed to point with the tip of their right big toe at a target (with the width W) placed on the floor in front of the subject at a certain distance, D. As such, the task involved performing a single discrete movement. The instruction given to the subjects was typical for Fitts' paradigm: "be as fast and as accurate as possible in your pointing movement". After the movement, the subjects were instructed to keep the final position of the right foot for about 1 s. Six different target distances (D = 10, 20, 40, 60, 80, and 100 cm) and five target widths (W = 2, 4, 6, 8, and 10 cm) were used resulting in 30 different target conditions with indices of difficulty, ID, $\mathrm{ID} = \log_2(2D/W)$ (Fitts 1954), varying from 1.00 to 6.64. Target distance was measured to the middle of the target. Within each condition, the subject performed at least 15 trials. The conditions were presented in a pseudo-random order, while the trials within a condition were blocked. The subjects performed 5–6 practice trials prior to each condition.

Each trial started with the subject standing in the initial position. The computer generated a sound signal (a beep). The subject was free to initiate the step at any moment in a self-paced manner within 5 s after the beep. Only one error (a trial that over- or undershot the target) was accepted per condition (a maximum of 7% of error per condition over accepted trials). In case another error was observed, the subject immediately repeated that trial. No more than 20 trials were necessary to complete each condition for all subjects, i.e. to record 15 acceptable trials. Between conditions, the subjects could rest or walk around, as they preferred; fatigue was never an issue.

Data analysis

Data analyses were performed using the Matlab 6.5 software (Mathworks Inc.). All the data were digitally low-pass filtered at 10 Hz using a fourth order, zero-lag Butterworth filter. The kinematic data were analyzed only in the sagittal plane (the main plane of movement). The time when the movement started (t_0) for each marker was defined as the instant when the tangential velocity of that marker reached 5% of its maximum value during that particular trial. The time when the movement ended (t_{END}) was defined as the time when the tangential velocity of the marker placed over the big toe reached 5% of its maximum value. Two groups of events were analyzed. The first group related to postural adjustments that occurred prior to the earliest t_0 across all markers. Events after that time were considered as related to the movement itself.

Movement time was always defined as the time between t_0 and t_{END} of the marker on the tip of the big toe. Movement amplitude was calculated as the distance between the positions of the big toe marker in the anterior–posterior direction at t_0 and t_{END}. Movement variability was estimated using the so-called effective target width (W_{E}), which was computed as four times the standard deviation (SD) of the movement amplitude across 15 trials within a condition. Note that W_{E} corresponds to an interval of approximately ±2SD that contains about 95% of the data assuming its normal distribution. Mean movement speed across trials, S, was calculated as the ratio between mean movement amplitude, A, and mean movement time, MT: $S = A/\mathrm{MT}$.

Changes of the ground reaction force in the AP direction (ΔF_{AP}) and of the COP location ($\Delta \mathrm{COP}_{\mathrm{AP}}$) in the AP direction at t_0 were computed with respect to the baseline values of these variables (the mean values within the time period between 1.5 and 0.5 s prior to t_0). Subsequently, variability of ΔF_{AP} and $\Delta \mathrm{COP}_{\mathrm{AP}}$ was quantified using a similar procedure to the movement variability estimation described earlier, that is, 4SD of the values of these variables across trials within a condition was used as a variability index. Before across-subjects comparison, the ΔF_{AP} data were normalized using the subject's body weight (BW).

Statistics

Standard statistical tools were used. Means and standard deviations were computed for outcome variables. One-sample t-tests with Bonferroni adjustment for multiple comparisons were performed to test if the movement amplitudes achieved by the subject were different from the prescribed ones. Pearson's chi-square (χ^2) was performed to test the effect of target distance and width on the order of marker involvement during movement initiation. Two-way repeated-measures ANOVA was performed to test the effects of the target distance (six levels) and target width (five levels) on the dependent variable, movement time. When the sphericity assumption (tested with the Mauchly test) for the ANOVA was not met, the Huynh-Feldt correction for the degrees of freedom was applied. Post hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons. Linear regressions were performed by the method of least squares, and the correlation coefficient was used to indicate the goodness of fit. Note that some values of ID were more common than others. However, we always performed analyses across a set of IDs, not within an ID, and all regression analyses were performed over sets of data where each ID was represented only once. However, the non-uniform representation of IDs across conditions might create a bias in some of the analyses. A significance level of 0.05 was used for all statistical tests, which were performed in SPSS 13.0 software (SPSS Inc.).

Results

All subjects successfully performed the step task for all target distances (D) and widths (W). Figure 1 shows exemplary time series of the center of pressure (COP) and force in the AP and ML directions as well as marker trajectories in the AP direction for the target distances 10 and 100 cm and target widths 2 and 10 cm averaged across trials for a representative subject. The trials were aligned by the first detectable motion of the marker placed over the right toe (see "Materials and methods").

On average, the subjects slightly overshot the target distance by less than 10%: the movement amplitudes were on average (±SD) 12.4 ± 0.8, 22.6 ± 0.5, 42.5 ± 0.7, 62.6 ± 0.8, 81.9 ± 0.4, and 101.4 ± 0.7 cm (for the prescribed distances 10, 20, 40, 60, 80, and 100 cm, respectively). The amount of overshoot had a tendency to decrease with movement amplitude if quantified relative to the distance; however, in absolute units this overshoot remained approximately constant between 1 and 3 cm. One-sample t-tests revealed that the actual movement amplitudes were significantly different from the respective prescribed distances for the targets at 10 and 20 cm, and they were not different for the remaining distances [10 and 20 cm: $t(9) > 4.77$, $P < 0.01$ and 40, 60, 80, and 100 cm: $t(9) < 1.5$, $P > 0.1$].

Two strategies to perform the task

Qualitatively, we observed two kinematic patterns of movements that showed modulation with the target distance. For close targets (10 and 20 cm), the subjects performed a pointing task with the tip of the big toe. To do the pointing, they first transferred the body weight to the left foot and then moved the right leg forward to reach towards the target without transferring the weight back to the right foot. For far targets (40 cm and more), the subjects made a step similar to fast gait initiation: The subjects first transferred the body weight to the left foot and inclined the trunk forward and then moved the right leg forward to step on the target transferring their weight to the right foot. Note that the two strategies were observed under the same explicit instruction to point with the tip of the right big toe at the target (see "Materials and methods").

Depending on the strategy, the first marker to move was either on the knee (the first strategy, "pointing") or on the shoulder (the second strategy, "stepping"). Figure 2 shows the most frequent marker (the statistical mode across subjects) that moved first as a function of movement distance and the timing of this marker movement initiation with respect to t_0 (for each marker, the moment of motion initiation was defined as the instant when the tangential velocity of the marker reached 5% of its maximum value during that particular trial, see "Materials and methods"). Curiously, among the body parts being monitored, the marker on the big toe was always the last to initiate motion [cf. proximal-to-distal pattern in Hasan and Karst (1989)]. Considering all trials, the movement was initiated with the shoulder marker (66% of the trials), or with the knee marker (24% of the trials), or yet with the hip marker (10% of the trials). There was a significant effect of target distance on the order of marker involvement during movement initiation ($\chi^2(10) = 164$, $P < 0.001$) and no effect of target width ($\chi^2(8) = 1.04$, $P = 0.998$). For the smaller distances (10 and 20 cm, with the exception of one target width at 20 cm), the movement was initiated by the knee marker approximately 155 ± 20 ms before the big toe moved (t_0), while for the larger distances (40 cm and more) the shoulder marker was the first to move, on average 540 ± 30 ms before t_0 (see Fig. 2).

Scaling of movement time

Figure 3a shows movement time (MT, the time between t_0 and t_{END} of the marker on the tip of the big toe, see "Materials and methods") averaged across subjects versus index of difficulty ($ID = \log_2(2D/W)$). Due to the experimental design, the highest IDs were achieved at the largest target distances, which led to the longest movement times. One can observe that MT scaled with both distance (D) to the target and target

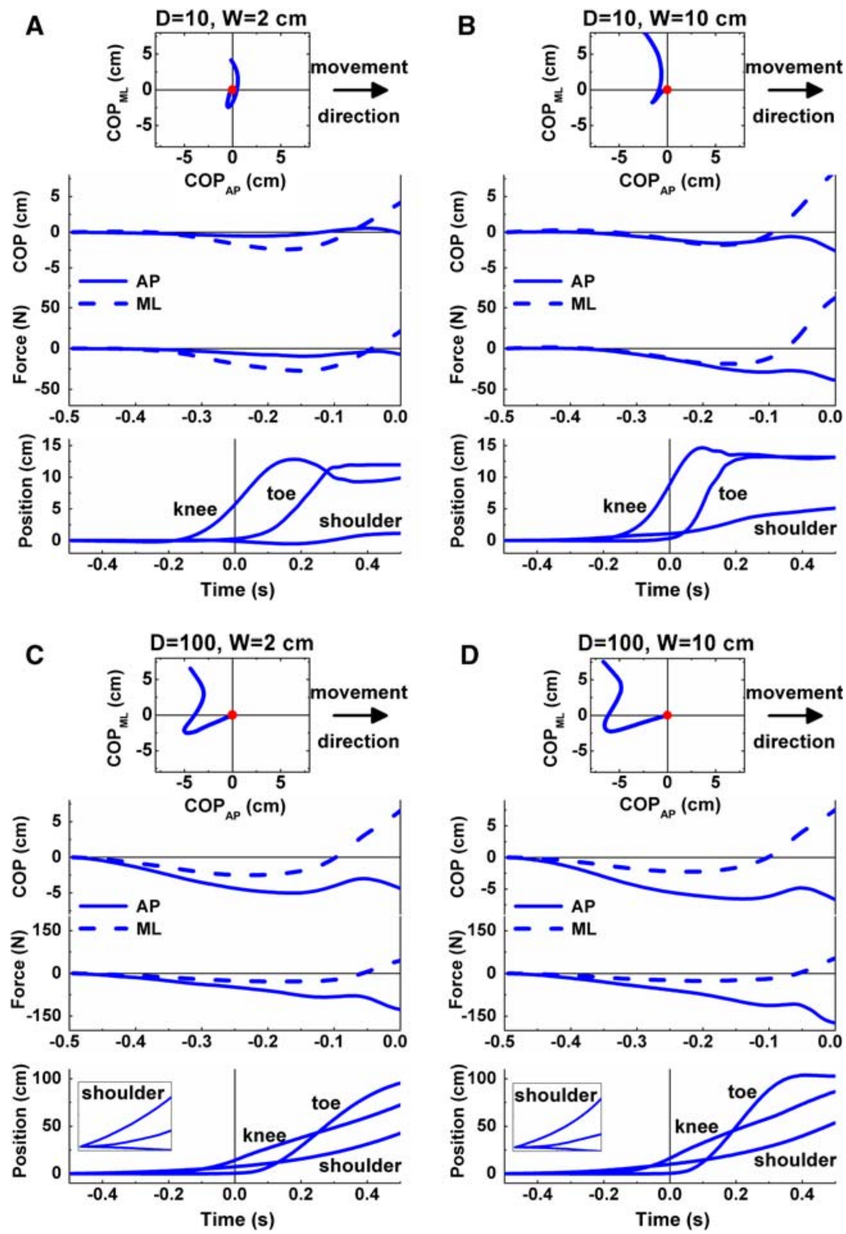

Fig. 1 Exemplary time series of the center of pressure (COP) and force in the anterior–posterior (AP) and medio-lateral (ML) directions, and marker trajectories in the AP direction for the target distances (*D*) of 10 and 100 cm and the target widths (*W*) of 2 and 10 cm averaged across trials performed by a representative subject. Note that the COP and force time scales are different from the kinematic time scale. The *inserts* at the bottom of plots **c** and **d** show zoomed plots of the initial part of the movement. For better visualization, all the data were set at zero at 0.5 s before the movement initiation

width (*W*). There were significant main effects of both *D* and *W* on MT [$F(5, 45) = 246$, $P < 0.001$ and $F(1.33, 12.0) = 19.7$, $P < 0.001$, respectively), and a significant interaction between *D* and *W* was also observed [$F(17.4, 156) = 246$, $P < 0.001$]. The post hoc comparisons revealed that all the different *D* resulted in significantly different MT ($P < 0.005$) with the exception of the pair of 10 and 20 cm, which led to similar MT ($P = 0.16$). In addition, all the different *W* resulted in significantly different MT ($P < 0.05$) with the exception of the pairs 2 and 4 cm ($P = 1$) and 8 and 10 cm ($P = 0.07$) which resulted in similar MT.

If all the data are considered (all combinations of *D* and *W*), one can observe a non-linear relationship between MT and ID. However, within the same target distance, MT was linearly related to ID as shown in Fig. 3a by the linear regressions between MT and ID for each target distance across target widths. The data were fitted using Fitts' equation (Fitts 1954): $MT = a + b \times ID$ and the correlation coefficients varied from 0.91 to 0.98 (P values <0.05). There was an increase in the slope of the regression lines with an increase in *D*, i.e., a similar increase in ID resulted in longer movement times at larger target distances. Figure 3b shows the values of '*a*' and '*b*' coefficients of the regression lines shown in Fig. 3a versus target distance. Indeed, the slope (*b*) of the linear fits shown in Fig. 3a is linearly proportional to the target distance ($r = 0.96$, $P < 0.01$) while '*a*' does not show a significant linear relation to the target distance ($r = -0.46$, $P > 0.3$).

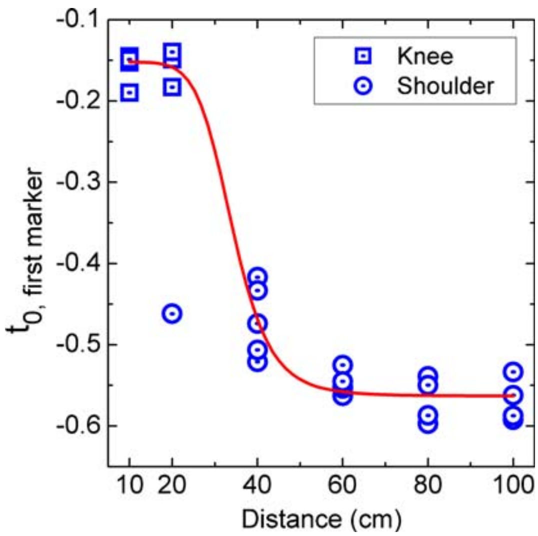

Fig. 2 The most frequent marker (the statistical mode across subjects) that moved first as a function of movement distance and the timing of this marker movement initiation with respect to the big toe movement ($t_{0,\text{first marker}}$). The different points at the same distance represent the different target widths. The *line* represents a logistic curve fitted to the data using the Levenberg-Marquardt algorithm (the datum represented by a circle at the 20-cm distance was treated as an outlier and not considered in the fitting)

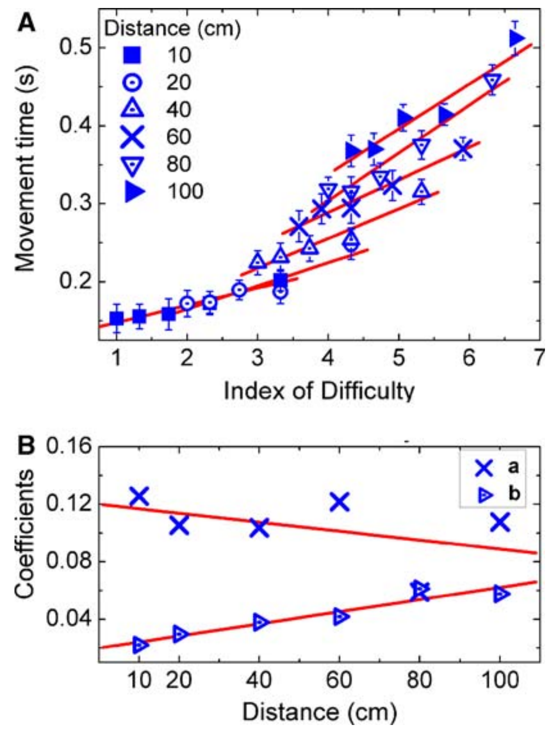

Fig. 3 **a** Mean (±1SE) movement time (MT) versus index of difficulty (ID) across subjects. The *symbols* represent the different target distances. The *straight lines* represent the best fits by least squares for each target distance with the equation $\text{MT} = a + b \times \text{ID}$. **b** *a* and *b* coefficients of the regression lines for each target distance shown in **a** versus target distance. The *straight lines* represent the best fits by least squares

Movement time is not related to leg length across subjects

The results shown in Fig. 3 suggest that target distance had a stronger effect on MT than target width. This is indeed verified in Fig. 4a where MT is shown as a function of target distance (averages across target widths for all subjects); MT shows a linear dependence on D. The correlation coefficients of the regression lines varied from 0.97 to 1 (P values <0.001). Different subjects showed different relations between MT and D but all these relations were linear. This difference could be expected due to the different leg lengths among subjects hence it is known that step length scales with the subject's leg length during walking (Winter 1991). Figure 4b shows MT versus D normalized by the subject's leg length. Contrary to expectations, this normalization did not eliminate the across-subjects differences, while mean MT averaged across D values was not related to leg length ($r = -0.28$, $P > 0.4$).

Movement variability is proportional to movement speed

Figure 5 shows the effective target distance, W_E, (4SD of the movement amplitude across trials) versus the mean movement speed, S, (the ratio between mean movement amplitude and mean movement time across trials) averaged across subjects. There was a significant linear relation between effective target distance and movement speed: $W_E\ (\text{cm}) = 3.32 + 0.015S\ (\text{cm/s})$, $r = 0.88$, $P < 0.0001$. Although the data for different effective target distances had different speed ranges, they could be all fitted with the same linear regression.

Variability prior to movement initiation is related to movement variability

We observed that movement variability was related to movement speed across the distances and target widths. Now, we will investigate if the variability in anticipatory postural adjustments was related to the variability in movement performance. First, we will test if variability in the changes of the ground reaction force in the AP direction (ΔF_{AP}) and of the COP shift in the AP direction (ΔCOP_{AP}) prior to movement initiation was related to movement speed. As described in "Materials and methods", the variability of ΔF_{AP} and ΔCOP_{AP} was estimated as four times the standard deviation of the values of these variables across trials within a condition. Figure 6 shows indices of variability

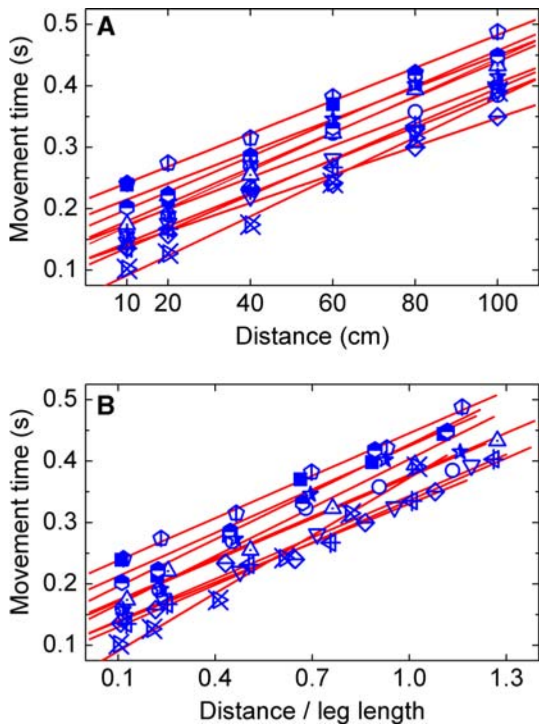

Fig. 4 **a** Mean movement time versus target distance averaged across target widths for all subjects. The *symbols* represent the different subjects and the *straight lines* represent the best fits by least squares for each subject. **b** Similar plot with the target distances normalized by the subject's leg length

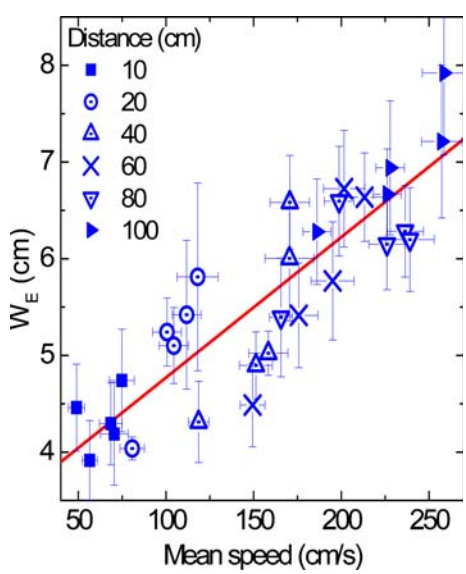

Fig. 5 Mean (±1SE) effective target width (W_E) versus mean movement speed (±1SE) across subjects. The *symbols* represent different target distances (see legend). The *straight line* represents the best fit by least squares

of the changes in the shear force and COP location (4SD ΔF_{AP} and 4SD ΔCOP_{AP}, respectively) versus mean movement speed (averaged across subjects data

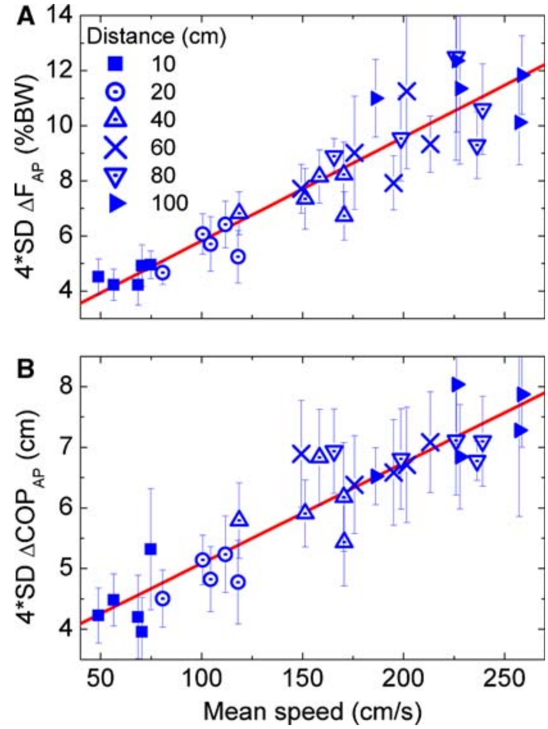

Fig. 6 **a** Mean (±1SE) force variability (four times the standard deviation of the changes in the ground reaction force in the anterior–posterior direction, 4SD ΔF_{AP}) and **b** mean (±1SE) COP variability (four times the standard deviation of the changes in the COP in the anterior–posterior direction, 4SD ΔCOP_{AP}) versus mean movement speed across subjects. Before across-subjects comparison, the force data were normalized by the subject's body weight (BW). The symbols represent different target distances (see legend). The *straight lines* represent the best fit by least squares. For the sake of clarity, the *error bars* of the mean speed data are not presented (see these error bars in Fig. 5)

are shown). Indices of both force and COP variability showed significant positive linear dependences on movement speed ($r = 0.92$, $P < 0.0001$ and $r = 0.91$, $P < 0.0001$, respectively).

The results shown in Figs. 6 and 5 suggest that force variability before and movement variability after movement initiation might be related. Figure 7 indeed shows that effective target width, W_E, shows a significant linear correlation with the force and COP variability ($r = 0.81$, $P < 0.0001$, $r = 0.74$, $P < 0.0001$, respectively).

Discussion

In this study we investigated how subjects, while standing, point with the big toe of the foot at targets of different size placed at different distances to test the following hypotheses: (1) movement time during foot pointing will scale linearly with ID during target width changes, but

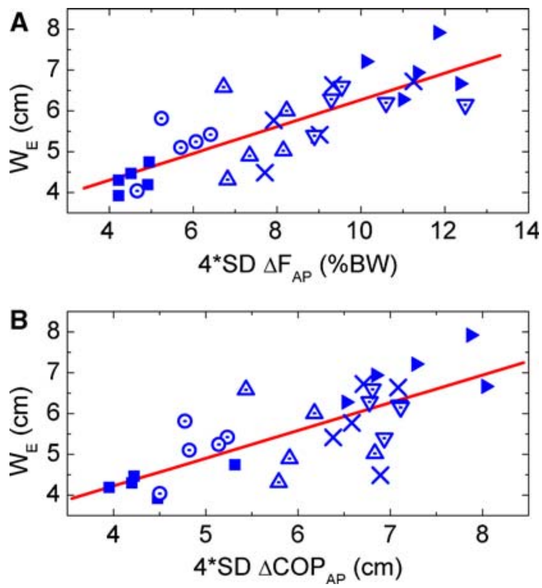

Fig. 7 Mean effective target width (W_E) versus mean force variability (four times the standard deviation of the changes in the ground reaction force in the anterior–posterior direction, 4SD ΔF_{AP}) and mean COP variability (four times the standard deviation of the changes in the COP in the anterior–posterior direction, 4SD ΔCOP_{AP}) across subjects. Before across-subjects comparison, the force data were normalized by the subject's body weight (BW). The *symbols* represent the different target distances from 10 to 100 cm (see legend in Fig. 6). The *straight lines* represent the best fits by least squares for each target distance. For the sake of clarity, the *error bars* of the data are not presented (see these error bars in Figs. 5 and 6)

the scaling will differ across movement distances; and (2) variations of movement time will be reflected in variations of postural preparation to foot motion. The results have shown that movement time during foot pointing movements scaled with both target distance (D) and target width (W), but the two dependences could not be reduced to a single function of W/D as dictated by Fitts' law (Fitts 1954). This finding supports the first hypothesis. It is more in line with reports on speed–accuracy trade-offs during voluntary postural sway (Danion et al. 1999; Duarte and Freitas 2005) and during tasks performed by standing subjects who moved one of the leg joints between two targets (Freitas et al. 2006). With respect to the second hypothesis, we found that changes in task parameters led to proportional variations in movement speed and indices of variability of the postural adjustments (APAs). Hence, the second hypothesis has been supported as well.

Speed–accuracy trade-off in tasks with a postural component

Fitts' law (Fitts 1954) is arguably one of the most established and universal relations in motor behavior. This law describes changes in movement time (MT) when a person tries to perform a fast and accurate action over a variety of distances and to a variety of targets. The linear relation between movement time and the index of difficulty has been experimentally confirmed over a variety of actions and in a variety of subject populations; however, violations to Fitts' law have also been observed (for a review see Plamondon and Alimi 1997). Following the original suggestion of Fitts (1954), it has been interpreted within the information theory framework, although alternative formulations and interpretations have also been offered (Crossman and Goodeve 1983; Meyer et al. 1988a; Gutman et al. 1993; Plamondon and Alimi 1997). All these formulations can be described with the equation (Duarte and Freitas 2005): $MT = a + b \times (D/W)^p$, where $0 < p < 1$. In some of these formulations, $W/2$ is used instead of W and a constant could be added to the D/W term. The logarithmic function, as in Fitts' law, can be viewed as a first order approximation of this type of power function.

Most early studies of motor variability that formed the experimental foundation for Fitts' law used discrete and cyclic motor tasks performed by the upper extremity (Fitts 1954; Fitts and Radford 1966). The very first experiment with the subjects performing a voluntary whole-body sway task under the typical instruction "be as fast and accurate as possible" led to unexpected results (Danion et al. 1999). The relations between target distance, target width, and movement time could not be reduced to a single equation as required by Fitts' law (Fitts 1954) or any other formulation based only on the ratio D/W. Later, this finding has been reproduced and generalized to other tasks performed by standing persons (Duarte and Freitas 2005; Freitas et al. 2006). All those tasks, however, were rather artificial. They involved moving the center of pressure or one of the postural joints between a couple of targets. In the present study, we used a much more natural task, fast and accurate foot motion. This movement for the longer distances may be compared to stepping on small stones while crossing a creek. The main finding of the previous studies has been confirmed: movement time scaled with target width, as predicted by Fitts' law, but a change in the distance changed the equation describing the scaling.

An early interpretation of these seeming violations of Fitts' law was that postural sway (spontaneous migration of the COP) reduced the effective target size and distorted the predicted scaling of movement time with W/D for a voluntary whole-body sway task (Danion et al. 1999; Duarte and Freitas 2005). Accordingly, Duarte and Freitas (2005) proposed a model where there is a component in movement variability that is independent of movement speed, somewhat similar to Gutman and collaborators' (1993) model where a speed independent component of variability was assumed for an upper limb movement. Duarte and Freitas (2005) interpreted this component in movement variability as being due to the spontaneous migration of the COP typical of the upright standing.

In a similar way to Duarte and Freitas (2005), the component in movement variability that is independent of movement speed for the present task can be estimated as the intercept of the linear regression of the effective width versus movement speed plot shown in Fig. 5. The linear intercept obtained was 3.32 cm, much higher than the value of 1.01 cm obtained by Duarte and Freitas (2005) for the voluntary whole-body sway task. However, if we consider that the task studied here, pointing/stepping with one leg, resembles unipedal standing more than bipedal standing; it is reasonable to suppose that the inherent noise in the task could be higher than during bipedal quiet stance. Accordingly, the COP standard deviation during unipedal stance is on average 0.63 ± 0.13 cm (Gravelle et al. 2002); this value multiplied by four (to get the effective target width as defined in "Materials and methods") results in 2.52 ± 0.52 cm, close to the obtained linear intercept. This match suggests that the seeming violation in the MT versus ID relation, shown in Fig. 4, can be attributed to the inherent variability present in the standing task.

Taking a broader view of the results, it is also possible that the presence of a postural task component is by itself an important contributor to the observed violation of the speed–accuracy trade-off. In particular, a number of earlier studies investigated the effects of varying movement distance and target size on reaction and movement time in experiments that varied initial posture of the moving limb (Klapp 1975; Mohagheghi and Anson 2001). Those studies have documented postural effects on both reaction time and movement time. In our study, the requirement not to lose balance at any time during the motion and at its completion places constraints on performance that interfere with the classical linear relation between MT and ID. An explicit formulation and exploration of these constraints with a deeper understanding of the inherent variability effect would be a topic for follow-up studies.

Brunt and colleagues (2000) investigated initiation of fast gait after a visual cue where the subjects were required to place their swing leg during the first step on targets of two different widths. In addition, the subjects were instructed to continue walking after the first step. There were two target widths of 6 and 12 cm placed at a distance of one gait step length for each subject. The authors observed that higher anterior–posterior forces were produced in the large-target condition but in contrast they did not observe an effect of target width on the time between movement initiation and the heel strike of the swing leg (the closest measure to movement time as defined here). In other words, in agreement with our present results, Brunt and colleagues (2000) observed an effect of accuracy constraint on movement preparation but they did not observed an effect of accuracy on the movement itself as observed here. These contradictory results might be due to the different ways movement time was defined and also due to the difference in the tasks performed.

Movement variability and postural preparation

When a standing person faces a task of performing a quick action, a sequence of events may be expected to have effects on movement characteristics such as average speed, movement time, and final position variability. First, movement speed, V (or movement time, MT) may be implicitly reflected in patterns of control variables to muscles involved in the explicit action component. These patterns may be based on such task parameters as distance and accuracy constraints (for example, target width): $V = f_1(D, W)$. According to a hypothesis suggested by Goodman (Gutman) and colleagues (1993), scaling of a timing parameter at the level of movement planning brings about the drop in V with an increase in D and a decrease in W. This hypothesis suggests, in particular, that the speed–accuracy trade-off may be reflected in the earliest motor phenomena, such as anticipatory postural adjustments (APAs). Note that an alternative view that Fitts' law is a result of feedback-based movement corrections (e.g., Meyer et al. 1988a) does not make this prediction.

APAs have been most commonly studies and quantified as early changes in the activation levels of postural muscles (reviewed in Massion 1992). These EMG changes are accompanied by changes in mechanical variables such as COP shifts and joint motion that follow EMG changes at an electromechanical delay but are still considered results of feed-forward control processes (Bouisset and Zattara 1987; Aruin and Latash 1995). In particular, COP shifts preceding stepping have been commonly described as APAs (Brunt et al. 1991). APAs prior to stepping involve COP shifts in both anterior–posterior and medio-lateral directions. In this study, however, we focused on adjustments in the anterior–posterior direction, the direction of the main task. This APA component is more relevant for testing the specific hypotheses.

For a selected movement speed, effects of the planned action on postural equilibrium may be estimated and used to generate APAs: APA = $f_2(V)$. For faster movements, larger APAs are expected and have been demonstrated (Lee et al. 1990). Actual movement variability, for example standard deviation of the final position (SD_{FP}) may be expected to reflect movement speed: $SD_{FP} = f_3(V)$. For faster movements, larger dispersion of the final position is expected and has been demonstrated (Schmidt et al. 1979).

Based on this chain of relations leading from task parameters to indices of postural preparation and performance, one can expect parallel scaling of movement velocity and final position variability and APA indices with changes in D and W. Such a scaling has indeed been observed in the study (Figs. 6 and 7) providing support for the suggested causal relations between task parameters, postural requirements, and indices of motor performance. The fact that the observed relations were valid over the whole range of (D, W) combination despite the apparent change in the strategy of performance, from a pointing action to a stepping action, may be viewed as additional support for the generality of the suggested sequence of causal relations.

Two strategies to perform the task

Before movement initiation, the subjects were standing with their weight approximately equally distributed between the two legs. To initiate the movement, they first transferred the body weight to the left foot. This phase is reflected in the COP shift shown in Fig. 1. The COP first moved towards the right foot and then moved towards the left foot to ensure the body weight transfer for all conditions. Such postural adjustments before leg movement are commonly observed in standing human subjects (Rogers and Pai 1995). However, after the transfer of the body weight to the left foot, the next movement phase varied as a function of the target distance. For close targets (10 and 20 cm), the subjects performed a pointing task with the tip of the big toe; they moved the right leg forward to reach towards the target without transferring the weight to the right foot. For far targets (40 cm and more), the subjects tilted the trunk forward and then stepped with the right foot on the target transferring their weight to the right foot. This latter strategy is similar to postural adjustments observed prior to fast gait initiation, and it has been well investigated (Rogers and Pai 1995; Brunt et al. 2000; Ito et al. 2003). Since the target distance and movement speed were related (see Fig. 5), the two observed strategies were also speed sensitive. At lower speeds, we observed the pointing strategy and at higher speeds, the stepping strategy. However, we think that the key factor for differentiating the two strategies was the target distance: at small distances the subjects were able to point at the target without having to transfer their weight to the moving leg. For larger distances (the transition to the new strategy was close to one step length), they had to transfer part of their weight to the forward leg because of biomechanical constraints to balance control.

Concluding remarks

To our knowledge, this is the first detailed study of how accuracy constraints affect initiation of leg movement in standing human subjects. Its potential importance is accentuated by the well known effects of accuracy requirements on gait parameters in the practice of posture and gait rehabilitation. In particular, tasks where patients are asked to step on lines/obstacles of different size and spaced by different distances are commonly employed in clinical rehabilitation (see for example Shumway-Cook and Woollacott 2001; Rogers et al. 2003). Besides, manipulation of target size is a common practice in teaching motor skills such as kicking a football. For example, children are sometimes taught with smaller footballs, which may have an effect on the task difficulty. An alternative would be to use balls of a standard size but lower inertia. The present experiment provides quantitative support for the use of accuracy constraints to manipulate task difficulty and both postural preparation to and execution of leg movements during standing. Future studies should investigate how the performance in such tasks is affected in individuals with posture and gait impairments.

Acknowledgments This work was supported by a FAPESP/Brazil grant (04/10917-0) to M. Duarte and by an NIH grant (NS-035032) to M. Latash. The authors are thankful to Siripan Siwasakunrat and Yun Wang for their help in the data collection.

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