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Fitts' Law in Early Postural Adjustments

M. Bertuccio¹, P. Cesari², and M.L. Latash³

¹Department of Biomedical Engineering, University of Southern California. 1042 Downey Way, DRB 140, Los Angeles CA 90089, USA. bertuccio@usc.edu

²Department of Neurological, Neuropsychological, Morphological and Movement Sciences, University of Verona. Via Casorati 43, 37131 Verona, Italy. paola.cesari@univr.it

³Department of Kinesiology, The Pennsylvania State University. 268N Recreation Building, University Park, PA 16802, USA. ml11@psu.edu

Abstract

We tested a hypothesis that the classical relation between movement time and index of difficulty (*ID*) in quick pointing action (Fitts' Law) reflects processes at the level of motor planning. Healthy subjects stood on a force platform and performed quick and accurate hand movements into targets of different size located at two distances. The movements were associated with early postural adjustments that are assumed to reflect motor planning processes. The short distance did not require trunk rotation, while the long distance did. As a result, movements over the long distance were associated with substantial Coriolis forces. Movement kinematics and contact forces and moments recorded by the platform were studied. Movement time scaled with *ID* for both movements. However, the data could not be fitted with a single regression: Movements over the long distance had a larger intercept corresponding to movement times about 140 ms longer than movements over the shorter distance. The magnitude of postural adjustments prior to movement initiation scaled with *ID* for both short and long distances. Our results provide strong support for the hypothesis that Fitts' Law emerges at the level of motor planning, not at the level of corrections of ongoing movements. They show that, during natural movements, changes in movement distance may lead to changes in the relation between movement time and *ID*, for example when the contribution of different body segments to the movement varies and when the action of Coriolis force may require an additional correction of the movement trajectory.

Keywords

Fitts' Law; Postural Adjustments; speed-accuracy trade-off; motor planning; reaching; Coriolis force

Corresponding author: Matteo Bertuccio, Ph.D., Postdoctoral Research Associate, University of Southern California, Department of Biomedical Engineering, 1042 Downey Way, DRB 208 Los Angeles, CA 90089-1111, Office: +1-213-740-1317, Fax : +1-213-740-6520, bertuccio@usc.edu.

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Author contributions

Matteo Bertuccio: developed apparatus and methods; performed the experiment; designed, performed, and reviewed statistical analysis; wrote first draft and reviewed the manuscript.

Paola Cesari: designed and reviewed statistical analysis; and reviewed the manuscript.

Mark L. Latash: conceived the experiment; developed apparatus and methods; designed and reviewed statistical analysis; and reviewed the manuscript.

Introduction

When humans perform movements over different distances (D) to targets of different size (W), movement time (MT) scales as a logarithmic function of the ratio D/W (reviewed in Meyer et al., 1988; Plamondon and Alimi, 1997). This general rule, known as Fitts' Law (Fitts, 1954; Fitts and Patterson, 1964), has been confirmed over a variety of actions performed in a variety of conditions. Traditionally, Fitts' Law is formulated as: $MT = a + b \log_2(2D/W)$, where a and b are empirical constants. Although the mechanisms that produce Fitts' Law are still under debate, the Law is likely to reflect processes at the level of motor planning (Gutman and Latash, 1993; Duarte and Latash, 2007; Bertuccio and Cesari, 2010).

Actions performed by standing persons are associated with two types of postural adjustments that are traditionally viewed as reflections of feed-forward processes, i.e., processes that happen at the stage of planning a movement. Early postural adjustments (EPAs) represent changes in muscle activation levels and contact forces with the environment seen a few hundred ms (up to 1 s) prior to the initiation of a voluntary action by a person involved in a postural task, for example in preparation to making a step or a voluntary whole-body sway (Crenna and Frigo, 1990; Krishnan et al., 2011; Klous et al., 2012). These adjustments differ from anticipatory postural adjustments (APAs) observed about 80–100 ms prior to a predictable perturbation, which may be associated with an action (Belenkii et al., 1967; Massion, 1992). The timing of APAs changes significantly under time pressure (in reaction time conditions) while the timing of EPAs remains unchanged (Wang et al., 2006; Klous et al., 2012). EPAs and APAs also differ in their functional role; the former generate adequate mechanical conditions for a planned action, while the latter produce forces and moments of force acting against those expected from the predictable perturbation (Klous et al., 2012).

Several recent studies explored potential role of motor planning processes in the Fitts' Law by quantifying characteristics of the postural adjustments seen prior to purposeful actions. Scaling of EPA magnitude with target size was observed in studies of pointing with the toes by standing persons (Duarte and Latash, 2007; Bertuccio and Cesari, 2010) corroborating the idea that Fitts' Law "originated" at the level of motor planning, and not exclusively at the level of corrections of an ongoing movement through visual feedback control (Meyer et al., 1988; Wu et al., 2010a). In those studies, however, the instructed action and the postural task shared muscle groups. So, the separation of the EPAs from the focal action looked artificial. To avoid this problem, we devised a study of fast pointing movements performed by the dominant arm of standing subjects to targets of varying size. Such movements are characterized by early changes in the activation of leg/trunk muscles and in the reaction forces acting on the body from the supporting surface. These postural adjustments start before the initiation of the instructed action and may be viewed as reflecting motor planning processes.

We purposefully selected two distances to the target, one that did not require the subjects to perform trunk rotation, and the other that did. For the shorter distance, different muscle groups produced the arm motion and the EPAs. For the longer distance, the necessity to perform trunk rotation forced the subjects to involve into the focal action muscle groups that also contributed to postural control. Our first hypothesis was that MT would scale with W for movements over both small and large distances, as predicted by Fitts' Law, and that this scaling would be reflected in changes in the magnitude of EPAs.

Note that during movements involving trunk rotation, two factors might affect movement kinematics, the relatively higher inertial load and the Coriolis force acting on the hand when the hand moves within a rotating environment (produced by the trunk rotation). Changes in

the inertial load typically lead to a close to linear scaling of peak movement speed (Gottlieb et al., 1989), which allows us to expect a change in the regression coefficient in the typical Fitts' equation. On the other hand, data in a recent study of subjects performing movements with different arm segments (Hoffmann and Hui, 2010) are more compatible with a change in the intercept in the Fitts' equation (see also Hoffmann, 1995).

The Coriolis force (F_{COR}) acts at an object that moves at a certain velocity in a rotating reference frame. If the object moves in a plane orthogonal to the axis of rotation, $F_{COR} = 2m \mathbf{V}$, where m is mass and $\mathbf{V}$ is the angular velocity of rotation of the reference frame. This force acts orthogonally to the velocity vector $\mathbf{V}$. The Coriolis force can lead to major perturbations of the movement kinematics when reaching movements are performed in a rotating environment (Lackner and DiZio, 1994). However, fast reaching movements involving voluntary trunk rotation show smooth trajectories even though the joint torques produced by the Coriolis force are comparable in magnitude with those produced by muscles (Bortolami et al., 2008). This observation implies that the central nervous system organizes reaching movements in such a way that effects of the Coriolis forces on movement kinematics are naturally incorporated into the action.

To our knowledge, effects of the Coriolis force on movement kinematics in a typical Fitts paradigm have not been studied. Based on the cited study of Bortolami et al. (2008), our second hypothesis was that, despite the action of the large, transient F_{COR} , Fitts' Law would be able to describe the dependence of MT on W , although the coefficients a and b in the Fitts' Law equation might change due to the involvement of body segments with different inertial properties in the movement performance (cf. Hoffmann and Hui, 2010; Hoffmann, 1995).

Experimental procedures

Participants

Ten male students served as subjects in this study. Average data for the subjects were (mean $\pm$ SD): 27 ± 4 years of age, 1.70 ± 0.06 m in height, 63.7 ± 7.4 kg in mass. All subjects were right-handed according to their preferential use of the hand during daily activities such as writing, eating and pointing. The subjects had no previous history of traumas or neuropathies to the upper and lower limbs. All subjects gave informed consent according to the procedures approved by the Office of Regulatory Compliance of the Pennsylvania State University.

Apparatus

A force platform (AMTI, OR-7) was used to record the moment of force around the vertical axis (M_z) and the horizontal component of the reaction force in the mediolateral direction (F_y). These two force-moment signals were chosen based on pilot trials that had shown most consistent postural adjustments before the movement in those signals. A desktop computer (Dell Inc., Round Rock, TX, USA, Optiplex 745) was used to collect data using the customized LabView-based software (LabView-5, National Instruments, Austin, TX, USA).

Kinematics of the right index finger was recorded using two reflective markers placed on the tip of distal phalange and on the proximal interphalangeal joint bony landmark of the right index finger. A four-cameras ProReflex system (MCU240, Qualisys Inc.) digitized the marker coordinates at 240 Hz. The force plate and the motion capture system were time synchronized using an electrical rectangular triggering pulse.

Procedures

The subject stood upright quietly on the force plate with the feet parallel to each other, 20 cm apart. The foot position was marked on the force plate and reproduced across all the trials. The left upper limb was relaxed along the left side of the trunk. The right elbow was flexed at 90° such that the forearm was parallel to the ground. The right hand was in a neutral pronation-supination position. The right digits were flexed to form a fist except for the index finger that was extended pointing straight ahead. A small wooden stick was used as a pointer; it was fixed with adhesive tape to the right index finger, parallel to the finger, such that the tip of the pointer was 6.6 cm away from the index finger tip. A target was placed to the left side of the subject at the same height as the right finger with the pointer.

Subjects were instructed to point with the tip of the pointer at the target with a single quick movement. The instruction given to the subject was typical of the Fitts paradigm: “move as quickly and as accurately as possible into the target”. There were two target distances 65 cm (D_1) and 100 cm (D_2) measured from the center of the target to the starting position of the pointer tip. For the smaller distance, the motion could be produced by the arm with minimal or no trunk rotation. For the larger distance, significant trunk rotation was necessary. For each distance, there were five different target widths (W), $W = 1, 1.5, 2, 4$ and 8 cm for D_1 ; $1.5, 2.3, 3.1, 6.2$ and 12.3 cm for D_2 . The target widths were chosen to match five indices of difficulty, $ID = \log_2(2D/W)$ (Fitts, 1954), which resulted to $ID = 4.0, 5.0, 6.0, 6.4$ and 7.0 . The targets were made of paper to produce minimal mechanical resistance if touched by the subject; they had a semicircular form and their diameter represented the target sizes. The task was to stop the pointer tip within the area formed by the semicircle while avoiding mechanical contact with the paper (Figure 1).

There were ten experimental conditions ($2 D \times 5 W$); within each condition the subjects performed 12 consecutive trials. The conditions were presented in a pseudorandom order, while the trials within a condition were blocked. The subjects performed 4–5 practice trials prior to each condition. Each trial started with the subject standing in the initial position. Subjects were required to initiate the action in a self-paced manner within a 5-s time interval after an auditory signal. There was no specific instruction to the subjects regarding head rotation: They were free to rotate the head with the trunk or to turn the head first, look at the target, and then perform the pointing movement. At the end of the movement, the subjects were requested to keep the final position for a few seconds. Two errors (trials that over- or undershot the target) were allowed per condition; in case an additional error was observed, the subject immediately repeated the entire condition. Between conditions, the subjects could rest or walk around for as long as they wished such that fatigue was never an issue.

Data analysis

Data analysis was performed using the Matlab 7.1 software (Matworks Inc., Natick, MA, USA). The kinematic data were digitally low-pass filtered at 15 Hz using a second order, zero-lag Butterworth filter. The kinematic position of the tip of the pointer was computed by extending the line passing through the two markers on the right index finger by the pointer length from the distal marker. The tangential velocity (V) of the pointer tip on the frontal plane was computed for each time sample. The instant of movement initiation (t_0) and termination (t_{END}) were defined for each trial as the time when the magnitude of V crossed 5% of its maximal value prior to and after its peak value (V_{PEAK}) respectively.

Movement time (MT) was defined as: $MT = t_{END} - t_0$. Movement amplitude was calculated as the actual distance between the positions of the tip of the pointer at t_0 and t_{END} . The coordinate systems of the force plate (x, y, z) and of the motion capture system (X, Y, Z) were aligned such that the relative axes were parallel to each other (see Figure 1).

To quantify the effects of target width on the kinematics of the pointer we computed the symmetry index (I_{SYM}) of the bell-shape velocity profile from t_0 to t_{END} . The index was measured as the ratio of the deceleration time, from the time at V_{PEAK} to t_{END} (T_{DEC}), to the acceleration time, from t_0 to the time at V_{PEAK} (T_{ACC}): $I_{SYM} = T_{DEC} / T_{ACC}$. $I_{SYM} > 1$ indicates a right-skewed velocity profile, while $I_{SYM} < 1$ indicates a left-skewed profile.

The early changes in M_z and F_y were quantified as the difference between their baseline values (average M_z and F_y value from 0 to 500 ms from the start of the trial) and the maximum or minimum peak value of the signal before t_0 . Then, these values, DM_z and DF_y , were normalized by the subject's body weight and height for DM_z and by body weight only for DF_y . The M_z (F_y) onset time, t_{Mz} (t_{Fy}) was detected as the instant when M_z (F_y) deviated from its baseline value by 5% of DM_z (DF_y). The difference between t_{Mz} (t_{Fy}) and t_0 was defined as the duration of postural adjustment for M_z and F_y respectively, DT_{Mz} and DT_{Fy} . Besides, the time between t_{Mz} and t_{Fy} and the maximum or minimum peak value before t_0 of M_z and F_y respectively were also computed ($DT_{Peak-Mz}$ and $DT_{Peak-Fy}$). The main outcome variables are illustrated in Fig. 2.

Statistics

Statistical analysis was performed using SPSS 16.0 (SPSS Inc, Chicago, IL, USA). Descriptive statistics was used to compute the means and standard deviations for the outcome variables. In order to test the main hypotheses related to the Fitts' Law, two-way repeated-measures ANOVAs, with the factors *Distance* (two levels, D_1 and D_2) and *ID* (five levels, $ID = 4.0, 5.0, 6.0, 6.4$ and 7.0), were performed on each dependent kinematic outcomes (MT , V_{PEAK} and I_{SYM}). To test the hypothesis that the scaling of MT , over D and W , would be reflected in changes of EPA magnitude and timing, two-way repeated-measures ANOVAs, *Distance* (two levels) $\times$ *ID* (five levels), were performed on the EPA variables (DM_z , DF_y , DT_{Mz} , DT_{Fy} , $DT_{Peak-Mz}$ and $DT_{Peak-Fy}$). Note that the *ID* factor had five levels since the target widths were chosen to match the *ID* values between D_1 and D_2 (see Procedures section for details). The Mauchly test was used to validate the repeated-measures ANOVAs; in case the sphericity assumption was not met, the Huynh-Feldt correction for the degrees of freedom was applied. Pairwise comparisons with Bonferroni corrections were used to explore significant effects. Linear regressions were performed by the method of least squares, and the correlation coefficient was used to indicate the goodness of the fit of the kinematic and EPA variables as a function of *ID*s. A significance level of 0.05 was used for all statistical tests.

Results

All subjects performed the task successfully; each subject had no more than a total of 5% of inaccurate movements in the entire experiment. Only one subject was requested to repeat a single condition due to more than 2 inaccurate movements within that condition. On average, the subjects slightly overshot the target along the movement direction: The movement amplitudes were on average ($\pm$ SD) 66.0 ± 3.6 and 100.6 ± 5.9 cm for the D_1 (60 cm) and D_2 (100cm) distances respectively. The trials were aligned by the first detectable motion of the pointer (t_0 , see Methods for details). Figure 3 shows the displacement and velocity of the pointer, as well as F_y and M_z profiles for twelve trials performed by a representative subject in conditions $\{D_1; ID = 4.0\}$ and $\{D_2; ID = 4.0\}$. Note the consistency of both kinematic and kinetic time profiles across the individual trials.

The scaling of movement time with *ID*

Movement time (MT) scaled linearly with *ID* for the data averaged across subjects as shown in Figure 4 (the top panel). Note that the regression line for the longer distance (D_2) is

shifted upwards compared to the regression line for D_1 . On average, $MT(\pm SD)$ was 0.54 ± 0.05 and 0.64 ± 0.04 s for D_1 and D_2 , respectively. Two-way ANOVA, $Distance \times ID$ on MT showed significant effects of both factors [$F_{(1,9)} = 23.93$, $p < 0.001$ and $F_{(4,9)} = 11.62$, $p < 0.001$, respectively] without an interaction. The pair-wise comparisons revealed that the different ID s resulted in significantly different MT values ($p < 0.05$) between $ID = 4.0$ and $ID = 5.0$, 6.0 and 7.0 .

The data for each distance were fitted with the Fitts' Law equation (Fitts, 1954; Fitts and Peterson, 1964): $MT = a + b \cdot ID$. The correlation coefficients were 0.98 and 0.99 ($p < 0.01$) for the D_1 and D_2 respectively. A paired t -test revealed a significant difference ($t_{(9)} = 4.36$, $p < 0.01$) between the intercepts a : 0.33 ± 0.13 s for D_1 and 0.47 ± 0.13 s for D_2 . No statistical differences were found between the slopes of the regression lines: 0.037 ± 0.028 and 0.029 ± 0.033 for D_1 and D_2 respectively.

Peak velocity

On average, peak velocity, V_{PEAK} , was 3.42 ± 0.25 and 4.18 ± 0.40 m/s for D_1 and D_2 respectively. There were significant main effects of both $Distance$ and ID on V_{PEAK} [$F_{(1,9)} = 15.05$, $p < 0.01$ and $F_{(4,9)} = 12.70$, $p < 0.001$, respectively] without an interaction. The pair-wise comparisons revealed that the different ID s resulted in significantly different V_{PEAK} ($p < 0.05$) between $ID = 4.0$ and $ID = 5.0$, 6.0 , 6.4 and 7.0 . V_{PEAK} scaled linearly with ID as shown in Figure 4 (in the middle) for each target distance. The correlation coefficients were 0.95 and 0.97 ($p < 0.05$) for the D_1 and D_2 respectively.

Symmetry Index

The velocity profile of the pointer was consistently right-skewed among subjects and target widths. On average, symmetry index ($ISYM$), was 1.82 ± 0.54 and 1.60 ± 0.54 for D_1 and D_2 respectively. There were significant main effects of both $Distance$ and ID on $ISYM$ [$F_{(1,9)} = 5.50$, $p < 0.05$ and $F_{(4,9)} = 6.92$, $p < 0.001$, respectively] without an interaction. The pair-wise comparisons revealed that the different ID s resulted in significantly different $ISYM$ ($p < 0.05$) between $ID = 4.0$ and $ID = 7.0$, 5.0 and 7.0 . The $ISYM$ linearly correlated with ID for D_2 ($r = 0.99$, $p < 0.001$) while the correlation with D_1 was just under the significance level ($r = 0.85$, $p = 0.065$) (Figure 4 at the bottom).

The moment of force (M_z) and horizontal ground reaction force (F_y)

Across conditions, subjects showed qualitatively similar smooth time profiles for M_z and F_y (see Figure 3). The first peak, for both F_y and M_z , occurred prior to the movement initiation (t_0), while the second one (of a different sign) was seen during the movement. The first F_y peak was directed against the direction of movement, while the second peak was in the movement direction; the first peak of M_z was in the clockwise direction while the second peak was in the counter-clockwise direction.

On average, the magnitude of the first M_z peak (DM_z) normalized by the product of the subject's weight and height was (mean $\pm$ SD) 0.010 ± 0.003 and 0.015 ± 0.004 for D_1 and D_2 respectively. There were significant main effects of both $Distance$ and ID on DM_z [$F_{(1,9)} = 27.58$, $p < 0.01$ and $F_{(4,9)} = 6.83$, $p < 0.001$, respectively] without an interaction. The pair-wise comparisons revealed that the different ID s resulted in significantly different DM_z ($p < 0.05$) only for the pair $ID = 5.0$ and 7.0 . There was a close to linear drop in DM_z with ID for each distance as shown in the top panel of Figure 5. The correlation coefficients were 0.91 and 0.97 ($p < 0.05$) for D_1 and D_2 respectively.

The onset of the M_z changes (DT_{Mz}) was, on average, 0.622 ± 0.097 and 0.622 ± 0.094 s before the initiation of movement for D_1 and D_2 respectively. There were no effects of

Distance and *ID* on this index. The first M_z peak ($DT_{Peak-Mz}$) was, on average, reached 0.171 ± 0.027 and 0.198 ± 0.034 s prior to t_0 for D_1 and D_2 , respectively. Significant main effects were found for both *Distance* and *ID* [$F_{(1,9)} = 9.80$, $p < 0.05$ and $F_{(4,9)} = 4.31$, $p < 0.01$, respectively], the interaction was close to significance level ($p = 0.057$). The pair-wise comparisons revealed a significant difference only between $ID = 6.0$ and 4.0 . The time to M_z peak increased linearly with *ID* for D_1 ($r = 0.90$, $p < 0.05$), but not for D_2 (Figure 5, at the bottom).

On average, the amplitude of the first F_y peak normalized by body weight prior to t_0 was 0.024 ± 0.016 and 0.045 ± 0.016 for D_1 and D_2 , respectively. There was a significant main effect of *Distance* [$F_{(1,9)} = 29.79$, $p < 0.001$] without other effects. The onset time of F_y changes (DT_{Fy}) was on average 0.678 ± 0.109 and 0.700 ± 0.110 s (no significant effects of *Distance* and *ID*). The time to the first F_y peak ($DT_{Peak-Fy}$) was 0.177 ± 0.055 and 0.210 ± 0.052 s for D_1 and D_2 respectively. It showed a tendency to increase with *ID*. There were significant main effects of both *Distance* and *ID* on $DT_{Peak-Fy}$ [$F_{(1,9)} = 8.55$, $p < 0.05$ and $F_{(4,9)} = 4.28$, $p < 0.01$, respectively], with a significant interaction [$F_{(4,36)} = 3.29$, $p < 0.05$]. The pairwise comparisons revealed differences between $ID = 4$ and $ID = 6.4$ and 7.0 ($p < 0.005$) for D_1 but no differences among *ID* levels for D_2 . The $DT_{Peak-Fy}$ had a tendency of linear correlation with *ID* for D_1 ($r = 0.80$, $p = 0.106$) (Figure 6, bottom).

Discussion

The results confirmed both predictions of our first hypothesis: Indeed, movement time (*MT*) scaled with target width (*W*) for movements over both small and large distances, as predicted by Fitts' Law, and this scaling was reflected in changes in the magnitude of the early postural adjustments (EPAs). With respect to the second hypothesis, only one of the two predictions was confirmed: We observed changes in the intercept, but not in the regression coefficients, of the Fitts equation (cf. Hoffman 1995; Hoffman and Hui 2010). The data for the two movement distances could not be described with a single linear equation $MT = a + b \log_2(2D/W)$. While the slopes (*b*) of the regression lines were similar across the two distances, the intercepts (*a*) were significantly higher for the longer distance. Further, we discuss implications of these findings for the feed-forward control of movements involving a postural component and for the origins of the Fitts' Law.

Feed-forward control and Fitts' Law

Several recent studies have linked speed-accuracy trade-off to predictive processes within the central nervous system (Duarte and Latash, 2007; Gawthrop et al., 2008; Bertuccio and Cesari, 2010; Radulescu et al., 2010). These conclusions fit well the hypothesis offered about 20 years ago that Fitts' Law originates at the level of movement planning (Latash and Gutman, 1993). Our study provides further support for this hypothesis. It extends the earlier observations on the scaling of postural adjustments observed in typical Fitts'-type experiments when the subjects were required to perform fast and accurate movements to targets while standing (Duarte and Latash, 2007; Bertuccio and Cesari, 2010). The postural adjustments are seen prior to the initiation of the instructed movement and reflect motor planning processes (cf. Massion 1992). Unlike the cited studies, in our experiment, Fitts' law was seen in characteristics of the EPAs, when the adjustments were produced by muscles different from those involved in the intentional pointing movements, as well as when the apparent postural adjustments contributed to the pointing movement (during movements involving trunk rotation).

The pointing movement performed while rotating the trunk was associated with substantial Coriolis forces that could perturb the planned hand trajectory. According to estimations of Bortolami et al. (2008), during movements at speeds comparable to those used in our

experiment, Coriolis forces are comparable in magnitude to those produced by muscle activations. Note that, because of the coupling of the body segments, the Coriolis forces produced perturbations acting not only on the hand but on other segments of the body including the trunk. This means that, at the level of mechanics, changes in the activation levels of the trunk and leg muscles had at least three task-related components. First, they had to counteract the trunk perturbations produced by the arm motion, as during movements over the shorter distance. Second, they had to compensate for the perturbing effects of the Coriolis forces. Third, they had to produce trunk rotation necessary for accurate pointing. The fact that characteristics of EPAs scaled with ID during movements over the larger distance suggests that all three components are integrated at the level of motor planning.

A change in movement distance is known by itself to lead to a close to linear scaling of peak velocity and acceleration of the movement (Corcos et al., 1988; Gottlieb et al., 1989, 1990). However, our data cannot be accounted for by such a simple rule. Indeed, if this were the case, one would expect an increase in the slope of the $MT(ID)$ function with distance, while we observed a change in its intercept, the slope stayed nearly unchanged. So, in our data, an increase in distance led not to a proportional increase in MT but to its increase by a nearly constant value similarly to earlier studies of Hoffman (Hoffman, 1995; Hoffman and Hui, 2010).

Postural adjustments prior to action

Traditionally, a single term “anticipatory postural adjustments” (APAs) has been used to describe adjustments seen prior to a planned action (for example, in preparation to stepping, Crenna and Frigo, 1990) and prior to an expected perturbation that might or might not be time-linked to a voluntary action (Belenkiy et al., 1967; Massion, 1992). Recent studies have documented major differences between these two classes of postural adjustments. In particular, early postural adjustments (EPAs) seen about 0.5 s prior to action initiation do not show consistent changes in their timing when the action is performed in a self-paced manner and under a typical simple reaction time instruction (Krishnan et al., 2011; Klous et al., 2012). In contrast, APAs seen about 100 ms prior to a quick action triggering a postural perturbation show major changes under the simple reaction time: Their timing shifts towards the action initiation time and the structure of the APAs is also changed (Lee et al., 1985; De Wolf et al., 1998). The functions of the two types of adjustments also seem to be different: EPAs create necessary or optimal mechanical conditions for the action to be performed, while APAs general time profiles of forces and torques that counteract those expected from the predictable perturbation. In our experiments, the timing of the postural adjustments, about 0.5 s prior to the initiation of the pointing movement, suggests that they represent EPAs. During movements over the longer distance, this idea fits well the mechanics of the task: The necessary counterclockwise body rotation (if looked from above) was associated with an early clockwise deviation of the moment of force (M_Z). On the other hand, during movements over the shorter distance that did not require trunk rotation, the function of these adjustments may fit better the description of APAs: To counteract mechanical effects of the action on the vertical posture.

Based on the similarity of the patterns of change in the shear force F_Y and moment M_Z between the two distances, and also invoking Occam’s razor, we feel that the postural adjustments can be safely described as EPAs. The difference between the two conditions may be apparent, not real: Note that similar patterns of control to the apparently focal and postural joints were reconstructed within the framework of the equilibrium-point hypothesis (Latash et al., 1998). In that study, a notion of a planned “movement of zero amplitude” for the postural joint was introduced. Such movements are controlled with equilibrium trajectories that may show large transient deviations but end close to the initial position. In principle, the control of such an action is not different from the control of an action when the

apparently postural joint moves purposefully over a certain distance. In our experiment, we can view movements over the shorter distance as a combination of a “zero amplitude” movement of the trunk and a large-amplitude movement of the arm. During longer distance movements, the arm continued to move over about the same distance, while the trunk produced a non-zero rotation. Performing the same actions in a simple reaction time paradigm could serve as the litmus test for this hypothesis, but unfortunately, for practical reasons, we did not include this condition.

Our hypothesis that the postural adjustments observed in our study represented EPA is corroborated by the finding that duration of the early changes in both force and moment of force (their onset time) did not depend on movement distance and index of difficulty. These findings are similar to those reported by Duarte and Latash (2007; Fig. 1). Note also that the timing of postural adjustments to stepping, a typical example of EPAs, has been reported to be similar across different speeds of stepping (Wang et al. 2006). In that study, the magnitude and time profile of the EPAs did change with the speed of stepping. Similarly, in our experiment, the F_Y and M_Z time profile changed with the index of difficulty ID (and associated changes in movement speed), particularly at low ID values.

Origins and characteristics of Fitts' Law

The original explanation by Fitts linked Fitts' Law to information theory (Fitts, 1954; Fitts and Peterson, 1964). Later, Meyer et al. (1988) suggested that movements to a small target consisted of a quick primary submovement followed by a sequence of corrective submovements. This idea received support in several later studies (Crossman and Goodeve, 1983; Walker et al., 1997; Novak et al., 2000; Elliott et al., 2001; Wu et al., 2010a). Scaling of characteristics of postural adjustments to action with ID does not fit this hypothesis very well. Indeed, if changes in movement time during movement to targets of different size are primarily defined by later submovements that follow an initial ballistic component, EPAs are not expected to show a dependence on ID . A few recent studies, however, have documented scaling of postural adjustments with ID in typical Fitts-type tasks (Duarte and Latash, 2007; Bertuccio and Cesari, 2010) corroborating the idea that Fitts' Law originated at the level of motor planning. This idea has also received support in a study by Wu et al. (2010b) who have shown that Fitts' Law holds in absence of visual feedback of the target and the limb during the task execution.

At this time, however, we cannot exclude that the scaling of movement time with ID also gets contribution at the level of corrections of an ongoing movement (Meyer et al., 1988). Indeed, the scaling of the symmetry index (I_{SYM}) of the velocity profile with ID suggests using on-line feedback control while approaching at the target.

Our current study also showed scaling of EPAs with ID while the muscles involved in the instructed action differed from those involved in postural adjustments, at least during movements over the shorter distance. We see the scaling of postural adjustments with target width during those movements as the strongest proof so far that the speed-difficulty trade-off described by Fitts' Law originated primarily at the level of motor planning. Obviously, the EPAs could not be corrected based on a predicted number of submovements. Otherwise, one would have to accept that movement inaccuracy was part of the action plan.

The classical Fitts' Law formulation predicts that changes in movement distance (D) and/or target width (W) should produce values of movement time that fit a single line on the MT vs. ID plane. Several recent studies have provided evidence of violations of this general law. For example, when standing subjects were asked to perform accurate body sway between pairs of targets under the typical Fitts instruction “be as quick and accurate as possible”, changes in the target width led to typical linear dependences of MT on ID . However, when

movement distance changed, the *MT* vs. *ID* lines fanned: The regression coefficient changed significantly (Duarte and Freitas 2005). These findings were interpreted as reflecting the large natural body sway that reduced the effective target width.

Our data show a different seeming violation of Fitts' Law: The linear regressions for the two movement distances were nearly parallel to each other and differed significantly in the magnitude of the intercept of the *MT*(*ID*) relation, while the regression coefficient stayed unchanged. In other words, movements over the larger distance took about 100–160 ms longer than those over the smaller distance to targets with the same *ID* values. Similar observations can be seen in figures published by Cerritelli et al. (2000) and by Hoffman and Hui (2010). We can offer a couple of speculative interpretations for this observation.

First, movements over the longer distance required trunk rotation – a movement involving a body segment with much higher inertia. This could by itself lead to an increase in movement time (Hoffman, 1995; Hoffman and Hui, 2010) reflected in the higher intercept in Fitts' equation. Second, movements over the longer distance were associated with poorly predictable Coriolis forces. One can speculate that in such conditions, a correction had to be introduced based on the actually emerging Coriolis forces, using proprioceptive and/or visual information leading to an increase in movement time that was consistent across the *ID* values.

Features of reaching movements performed by standing subjects under a typical Fitts instruction were studied by Bonnetblanc (2008). When the subjects pointed at targets placed beyond reach, they had to involve trunk flexion. In those conditions, the slope of the Fitts equation changed while the intercept changes were ambiguous, in contrast to our results. The author interpreted the findings as consequences of adding kinematic degrees-of-freedom to the task. The task used by Bonnetblanc is similar to our task in involving trunk motion in some conditions while it differs from our task in using trunk motion not associated with Coriolis forces. This may be one reason for the differences in the findings, although at this point assigning the difference in the results to Coriolis forces remains speculative.

In conclusion, our results provide support for the hypothesis that Fitts' Law emerges at the level of motor planning, not at the level of corrections of ongoing movements. They show that, during natural movements, changes in movement distance may lead to changes in the relation between movement time and *ID*, for example when the contribution of different body segments to the movement varies. Some of the results, however, point at a contribution of sensory-based feedback mechanisms. It seems feasible that an interplay of the feed-forward (planning) and feedback mechanisms produces what is known as Fitts' Law with the relative importance of the two mechanisms dependent on particular features of the task including its mechanics.

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Highlights

Early postural adjustments scale with movement amplitude and accuracy.

The relation between movement time and ID changes with the movement distance.

Fitts' Law emerges at the level of motor planning.

Figure 1.

Illustration of the experimental setup: A) The subject stood upright quietly on the force plate with feet parallel 20 cm apart, the left upper limb was relaxed along the left side of the trunk, while the right elbow was flexed forming an angle of 90° between the forearm and the upper arm such that the forearm was parallel to the ground. A target was placed to the left side of the subject at the same height as the right fingers, it had a semicircular form and the diameter represented the target size. The force plate axes X, Y, and Z corresponded to anterior-posterior, medio-lateral and vertical directions respectively. B) The task was to point with a single movement and stop within the area of the target positioned at two different distances ($D_1 = 65$ cm, and $D_2 = 100$ cm).

Figure 2.

A representative trial showing the velocity profile of the right index finger (top), the component of the ground reaction force in the medio-lateral direction (F_y) (middle) and the moment of force around the vertical axis (M_z , bottom). Time zero corresponds to the start of the movement. Outcome variables for early postural adjustments, such as the amplitude (ΔF_y , ΔM_z), onset (ΔT_{F_y} and ΔT_{M_z}) and the time to peak (ΔT_{Peak-F_y} , ΔT_{Peak-M_z}) of F_y and M_z , are illustrated.

Figure 3.

The time profiles of the pointer displacement (A), its tangential velocity profile (B), the shear force (F_y) (C) and the moment (M_z) (D) for $D_1 = 65$ cm and $D_2 = 100$ cm ($ID = 4$) are presented for the series of twelve individual trials performed within each of the two conditions by a representative subject. The trials were aligned by the first detectable motion of the pointer.

Figure 4. Mean movement time (MT , top), peak velocity (V_{PEAK} , middle) and symmetry index (I_{SYM} , bottom) averaged across subjects as functions of the index of difficulty (ID). Error bars are standard errors across subjects. The straight lines show the best fits by the least squares method for each target distance (D_1 – filled symbols and D_2 – open symbols).

Figure 5.

Mean magnitude of the first M_z peak (ΔM_z , top) and time to M_z peak (ΔT_{Peak-M_z} , bottom) averaged across subjects as functions of the index of difficulty (ID). Error bars are standard errors across subjects. The straight lines show the best fits by the least squares method for each target distance (D_1 – filled symbols and D_2 – open symbols).

Figure 6.

Mean magnitude of the first F_y peak (F_y , top) and time to F_y peak ($\Delta T_{Peak-Fy}$, bottom) averaged across subjects as functions of the index of difficulty (ID). Error bars are standard errors across subjects. The straight lines show the best fits by the least squares method for each target distance (D_1 – filled symbols and D_2 – open symbols).