Fitts’ Law in Early Postural Adjustments

M. Bertucco, P. Cesari AND M. L. Latash

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 Peterson, 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 (Cutman et al., 1993; Duarte and Latash, 2007; Bertucco 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, 1991; 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 (Belenkiy 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 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; Bertucco 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 sizes. 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 Fitts’ equation (see also Hoffmann, 1995).

The Coriolis force ($\text{COR}$) 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, $\text{COR} = 2m\omega V$, where $m$ is mass and $\omega$ is the angular velocity of rotation of the reference frame. This force acts orthogonally to the velocity vector $V$. 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 $\text{COR}$, Fitts’ Law would be able to describe the dependence of $MT$ on $W$, although the coefficients $a$ and $b$ in Fitts’ Law equation might change due to the involvement of body segments with different inertial properties in the movement performance (cf. Hoffmann, 1995; Hoffmann and Hui, 2010).

**EXPERIMENTAL PROCEDURES**

**Participants**

Ten male students served as subjects in this study. Average data for the subjects were (mean ± 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, Watertown, MA, USA) was used to record the moment of force around the vertical axis ($M_z$) and the horizontal component of the reaction force in the medio-lateral direction ($F_x$). 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-camera ProReflex system (MCU240, Qualysis Inc., Gothenburg, Sweden) 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 an 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 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 ($W$) 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) \text{ (Fitts, 1954), which resulted to } ID = 4.0, 5.0, 6.0, 6.4 \text{ 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 (Fig. 1).}

There were 10 experimental conditions (2D × 5W); within each condition the subjects performed 12 consecutive trials. The conditions were presented in a pseudo-random order, while the trials within a condition were blocked. The subjects performed four to five 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 (t0) and termination (tEND) 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 (VPEAK) respectively.

Movement time (MT) was defined as: MT = tEND − t0. Movement amplitude was calculated as the actual distance between the positions of the tip of the pointer at t0 and tEND. 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 Fig. 1).

To quantify the effects of target width on the kinematics of the pointer we computed the symmetry index (ISYM) of the bell-shape velocity profile from t0 to tEND. The index was measured as the ratio of the deceleration time, from the time at VPEAK to tEND (TDEC), to the acceleration time, from t0 to the time at VPEAK (TACC): ISYM = TDEC/TACC. ISYM > 1 indicates a right-skewed velocity profile, while ISYM < 1 indicates a left-skewed profile.

The early changes in Mz and Fy were quantified as the difference between their baseline values (average Mz and Fy value from 0 to 500 ms from the start of the trial) and the maximum or minimum peak value of the signal before t0. Then, these values, DMz and DFy, were normalized by the subject’s body weight and height for DMz and by body weight only for DFy. The Mz (Fy) onset time, tMz (tFy) was detected as the instant when Mz (Fy) deviated from its baseline value by 5% of DMz (DFy). The difference between tMz (tFy) and t0 was defined as the duration of postural adjustment for Mz and Fy respectively, DTMz and DTFy. Besides, the time between tMz and tFy and the maximum or minimum peak value before t0 of Mz and Fy respectively were also computed (DTpeak-Mz and DTpeak-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 Fitts’ Law, two-way repeated-measures ANOVAs, with the factors Distance (two levels, D1 and D2) and ID (five levels, ID = 4.0, 5.0, 6.0, 6.4 and 7.0.), were performed on each dependent kinematic outcomes (MT, VPEAK and ISYM). 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) × ID (five levels), were performed on the EPA variables (DMz, DFy, DTMz, DTFy, DTpeak-Mz, and DTpeak-Fy).

Note that the ID factor had five levels since the target widths were chosen to match the ID values between D1 and D2 (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...
such as the amplitude (the movement. Outcome variables for early postural adjustments, time to peak (ID), were on average (±SD) 66.0 ± 3.6 and 100.6 ± 0.4 s for D1 and D2, respectively. Two-way ANOVA, Distance × 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 pairwise comparisons revealed that the different IDs 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 Fitts’ Law equation (Fitts, 1954; Fitts and Patterson, 1964): MT = a + b/ID. The correlation coefficients were 0.98 and 0.99 (p < 0.01) for the D1 and D2 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 D1 and 0.47 ± 0.13 s for D2. No statistical differences were found between the slopes of the regression lines: 0.037 ± 0.028 and 0.029 ± 0.033 for D1 and D2 respectively.

Peak velocity

On average, peak velocity, V_Peak, was 3.42 ± 0.25 and 4.18 ± 0.40 m/s for D1 and D2 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 pairwise comparisons revealed that the different IDs 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 Fig. 4 (in the middle) for each target distance. The correlation coefficients were 0.95 and 0.97 (p < 0.05) for the D1 and D2 respectively.

Symmetry index

The velocity profile of the pointer was consistently right-skewed among subjects and target widths. On average, symmetry index (I_SYM), was 1.82 ± 0.54 and 1.60 ± 0.54 for D1 and D2 respectively. There were significant main effects of both Distance and ID on I_SYM [F(1,9) = 5.50, p < 0.05 and F(4,9) = 6.92, p < 0.001, respectively] without an interaction. The pairwise comparisons revealed that the different IDs resulted in significantly different I_SYM (p < 0.05) between ID = 4.0 and ID = 5.0, 6.0 and 7.0. The I_SYM linearly correlated with ID for D2 (r = 0.99, p < 0.001) while the correlation with D1 was just under the significance level (r = 0.85, p = 0.065) (Fig. 4 at the bottom).

The moment of force (Mz) and horizontal ground reaction force (Fx)

Across conditions, subjects showed qualitatively similar smooth time profiles for Mz and Fy (see Fig. 3). The first peak, for both Fy and Mz, 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 ± 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 [$F_{(1,9)} = 27.58$, $p < 0.01$ and $F_{(4,9)} = 6.83$, $p < 0.001$, respectively] without an interaction. The pair-wise comparisons revealed that the different IDs 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 Fig. 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 ($DT_{M_z}$) 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 ($DT_{Peak-M_z}$) 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 $D_2$ (Fig. 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 ($DT_{F_y}$) 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 ($DT_{Peak-F_y}$) was 0.177 ± 0.055 and

---

**Fig. 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 12 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.
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 $D_1$ ($r = 0.80$, $p = 0.106$) (Fig. 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 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. Hoffmann, 1995; Hoffmann 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 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; Bertucco 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; Bertucco 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 Hoffmann (Hoffmann, 1995; Hoffmann and Hui, 2010).

Postural adjustments prior to action

Traditionally, a single term “APAs” has been used to describe adjustments seen prior to a planned action (for example, in preparation to stepping; Crenna and Frigo, 1991) 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, 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 toward the action initiation time and the structure of the APAs is also changed (Lee et al., 1987; 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 (MZ). 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 FY and moment MZ 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., 1999). In that study, a
notion of a planned “movement of zero amplitude” for the
torial 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; Bertucco 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 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 Cerri et al. (2000) and
by Hoffmann 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 (Hoffmann, 1995; Hoffmann
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.

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 IO, 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.

AUTHOR CONTRIBUTIONS

Matteo Bertucco: 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.

Acknowledgment—This work was in part supported by the NIH grant NS-035032.

REFERENCES


(Accepted 22 November 2012)
(Available online 2 December 2012)