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Human Movement Science 22 (2003) 365–376
HUMAN MOVEMENT SCIENCE
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Impact forces cannot explain the one-target advantage in rapid aimed hand movements

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Received 7 January 2003; received in revised form 4 July 2003; accepted 7 July 2003

Abstract

A pointing movement is executed faster when a subject is allowed to stop at the first target than when the subject has to proceed to a second target ("one-target advantage"). Our hypothesis was that this is because the impact at the target helps to stop the finger when the finger does not have to proceed to a second target. This hypothesis would predict that the horizontal force at contact with the first target should be larger when there is only one-target. Modelling smooth movements with larger forces at contact using a minimum-jerk model, shows that the peak velocity is slightly higher and it occurs later during the movement when there is only one target. Although the one-target advantage was present in our experiment, the horizontal force at contact in the one-target condition was not larger than in the two-target condition. The time of the maximum velocity did not differ, but the maximum velocity was higher in the one-target condition. Thus our hypothesis is rejected, favouring a non-mechanical explanation of the one-target advantage.

PsycINFO classification: 2330
Keywords: One-target advantage; Impact force; Motor control

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0167-9457/$ - see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/S0167-9457(03)00050-2

1. Introduction

Numerous studies have reported that a rapid aimed hand movement to a target is executed faster if the hand is allowed to stop at the target, than if it has to proceed to a second target (Adam et al., 2000; Chamberlin & Magill, 1989; Christina, Fischman, Lambert, & Moore, 1985; Fischman, 1984; Fischman & Reeve, 1992). This so-called one-target advantage occurs regardless of the distance to be moved (either to the first target or to the second target; Adam et al., 2000), the direction of the second movement (except a reversal movement; Adam et al., 2000; Fischman, 1984), the number of targets (Smiley-Oyen & Worringham, 2001; Fischman, 1984) or the kind of movement (abduction or adduction; Helsen, Adam, Elliott, & Buekers, 2001). It is independent of eye movements (Adam et al., 2000) and remains constant over practice (Adam, Helsen, Elliott, & Buekers, 2001). The effect is about 8–15% of the movement time.

Understanding why the one-target advantage arises is not so easy. Several explanations exist. The one-target advantage has been explained by the need to prepare the second movement during execution of the first movement (Chamberlin & Magill, 1989), the need to have a more controlled first movement in order to execute the second one accurately (Fischman & Reeve, 1992) or a combination of both (Adam et al., 2000).

We propose another explanation, the deceleration hypothesis. This explanation is based on the notion that impact with the target is an important factor in the deceleration of the arm in single element aiming movements (Teasdale & Schmidt, 1991). Impact with the target leads to a force opposite to the direction of the movement and thus to deceleration of the hand. This means that less muscular force is needed for the same deceleration. This could influence the way in which the movements are controlled. When high velocities at impact are not a problem, impact with the target could passively provide a part of the deceleration, so that the same muscular forces yield a shorter deceleration time.

There is indeed some evidence that impact can influence movement characteristics. For instance, in the study of Adam, van der Bruggen, and Bekkering (1993) subjects had to slide a pen over a tablet to a target and either stop there, or return to the starting position. In both cases there were conditions with and without a mechanical stop at the target. Shorter movement time, higher peak velocity and lower percentage of the movement time spent decelerating (all to small targets) were found when subjects could use a mechanical stop at the target. This indicates that passive deceleration can indeed induce faster movements.

Adam et al. (1993, 1997) already suggested that passive deceleration, and thus large impact forces at initial contact with the first target in the one-target condition, could account for the one-target advantage in rapid aimed hand movements. In the two-target condition, large impact forces opposite to the movement direction are disadvantageous because they hinder the departure from the first target. Therefore subjects are more likely to actively slow down their movement to the first target.

This proposal can explain why the one-target advantage is not found for reversal movements (Adam et al., 1993; Lajoie & Franks, 1997), because the reaction force is in the same direction as the reversal movement so that the kinetic energy stored in deformation of the skin and of finger muscles can even be used to start the reversal movement (Guiard, 1993). When there is no second movement, the reaction force at the first target may cause the finger to bounce back a little towards the starting position, so there are limitations to its magnitude, perhaps explaining why subjects can be even faster for reversal movements (Lajoie & Franks, 1997).

Adam et al. (1997) tested the deceleration hypothesis by measuring the vertical impact force in a one-target condition and a two-target condition. They did not find differences in vertical impact force between the conditions, and therefore rejected the hypothesis. However their experiment is not the best test of the hypothesis based on the hypothesis of Adam et al. (1993), as the latter involved horizontal forces, whereas the 1997 experiment only measured vertical forces.

Could it be that it is not the vertical force, as measured by Adam et al. (1997), but the horizontal force (in the main direction of the movement) that is different for a one-target and a two-target condition? To determine whether this deceleration hypothesis could explain the one-target advantage we first investigated the consequences of having a different horizontal force at contact by changing the final deceleration in a minimum-jerk model for pointing (Flash & Hogan, 1985). We found that changes in the final deceleration could influence the movement time. We therefore had subjects perform one-target and two-target movements and measured the horizontal force at contact with the first target. However, measuring the deceleration and force at the end of the movement is difficult, because it depends on the details of how contact is made. We therefore also used the above-mentioned minimum-jerk model to predict the values of related kinematic measures that could be tested more easily. We did this for the deceleration hypothesis and for an alternative hypothesis in which a general increase in speed is responsible for the one-target advantage (Chamberlin & Magill, 1989; Fischman & Reeve, 1992; Adam et al., 2000). We compared the predicted values for both hypotheses with the experimental results.

2. Model for pointing

The minimum-jerk pointing model of Flash and Hogan (1985) describes a pointing movement with constraints at the beginning and the end of the movement. For a point-to-point movement the parameters are movement time, the initial and final positions of the finger, and a velocity and deceleration of zero at both the beginning and the end of the movement. Smeets and Brenner (1999) adapted this model with a non-zero deceleration at the end of the movement, and scaled that by the squared movement time to get an "approach parameter". The horizontal component of a pointing movement is then described as follows:

$$x(t_\mathrm{r}) = \left(\frac{1}{2}a_\mathrm{p}(t_\mathrm{r}-1)^2 + l(6t_\mathrm{r}^2 - 15t_\mathrm{r} + 10)\right)t_\mathrm{r}^3$$

where t_r is the relative time, l the horizontal distance between the targets, and a_p the approach parameter: the final deceleration scaled with the squared movement time. We define the end of the simulated the movement as the time the velocity is zero. We model three different movements: the two-target condition (same for both hypotheses), the impact condition (one-target condition according to the deceleration hypothesis) and the no-impact condition; the one-target condition according to the alternative hypothesis ("speed-hypothesis") that a general increase in speed (rather than a change in final deceleration) is responsible for the one-target advantage. For the two-target condition acceleration at contact should be zero, because the finger decelerates before contact and accelerates after contact. By its definition the no-impact condition also requires a zero acceleration at contact. We therefore used an approach parameter of zero at the end of the movement to the first target for these two conditions. In the impact condition on the other hand, it is indefinite what should happen after contact, so any final acceleration is possible.

To simulate our movements we used a one-target advantage of 10%. This is a moderate effect based on the percentages that were found in previous studies (Table 1, Adam et al., 2000). For a given MT and l we can calculate the peak velocity and the time of peak velocity when $a_p = 0$ (two-target condition, no-impact condition) as well as for any other value of a_p (impact condition). Thus we can predict the influence of any reduction in movement time and any value of a_p on the magnitude of peak velocity and its timing.

For the two-target condition and the no-impact condition the velocity and the acceleration at contact are always zero. Peak velocity is reached at 50% of the movement. The peak velocity is directly related to the movement time. The model predicts that for 10% less MT, the peak velocity in the no-impact condition will be 11% larger (see Fig. 1).

For the impact condition, the prediction depends on the value of $a_{p.}$ Increasing a_p results in a slightly higher peak velocity that is reached later (at up to 60% of the movement time rather than at 50% as in the two-target condition and in the no-impact condition). The maximal effect of impact is found for $a_p = 8l$. In that case and a one-target advantage of 10% the peak velocity increases slightly by 2.4% (see Fig. 1).

Having determined several kinematic parameters that would indicate whether an increase in the final deceleration or a general increase in speed accounts for the one-target advantage, we are ready to test our hypothesis experimentally. We let subjects tap one target with their index finger and either stop there or move on to a second target. We measured the movement of the finger and all components of the forces during contact with the first target.

3. Experimental methods

This study is part of an ongoing research program that has been approved by the local ethics committee. Ten subjects volunteered to take part in the study after being informed about what they would be required to do.

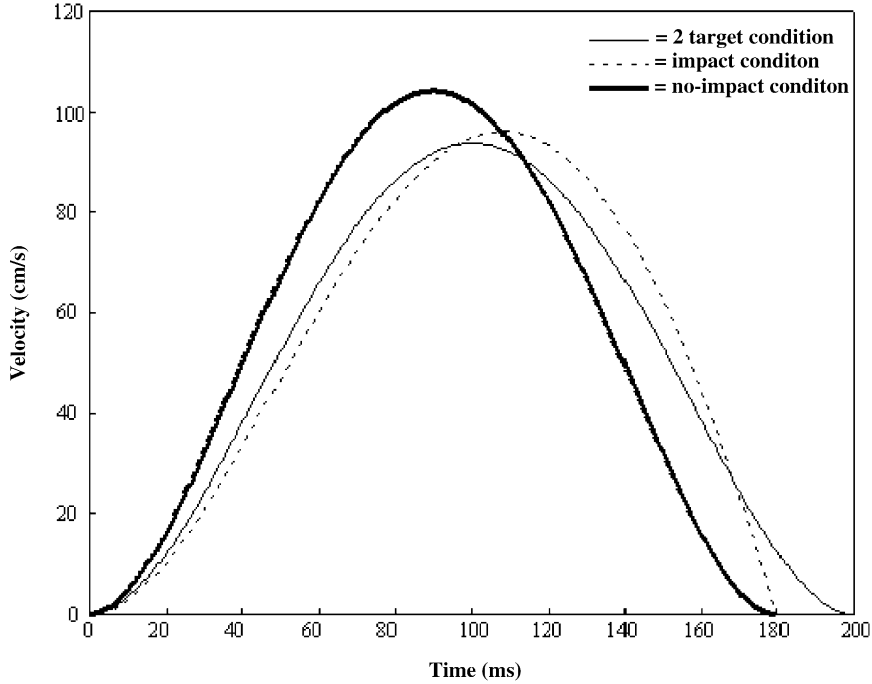

Fig. 1. Model predictions. The thin black line shows the horizontal velocity profile for the two-target condition as predicted by the minimum-jerk pointing model. The dashed line shows the predictions for the one-target condition according to the deceleration hypothesis (impact condition). The thick black line shows the predictions for the one-target condition according to the speed hypothesis (no-impact condition).

3.1. Set up

The set up consisted of a force sensor (ATI, Nano17 Ft) and two black plastic cylinders (starting target and second target) mounted on a wooden board such that the total surface was flat. The cylinders were the same size as the force sensor (17 mm diameter, 14.5 mm height). The starting position was the rightmost cylinder. The first target (force sensor) was located 10 cm to the left of the starting position. The second target (plastic cylinder) was located 10 cm to the left of the first target (Fig. 2). Subjects sat with their midline aligned with the position of the second target.

An IRED was placed on the nail of the subject's right index finger. Positions of this IRED were measured at 500 Hz with the Optotrak motion recording system (resolution 0.01 mm). The force and torque at the first target were measured in all three directions by the force sensor (resolution 0.025 N) at a sampling rate of 500 Hz.

The force sensor data were measured in synchrony with the movement data by means of the Optotrak Data Acquisition Unit. We determined the delay of

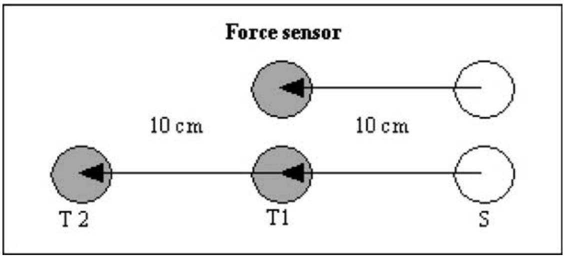

Fig. 2. Experimental set-up. Subjects moved their index finger from the starting point (S) to the first target (T1) and either stopped there (one-target condition) or moved on to the second target (T2, two-target condition).

the signal processing of the force sensor to be 8 ms, and corrected the data afterwards.

3.2. Procedure

Subjects were instructed to place their right index finger on the starting position. All movements were made from right to left. There were two different conditions, each performed in a separate block. After an auditory signal subjects had to move their index finger to the first target and either stop there (one-target condition), or strike it and move on to the second target (two-target condition). Emphasis was placed on executing the movement as fast as possible. They had to remain on the final target until a second auditory signal sounded.

To reduce errors, the experimenter removed the second target from the board in the one-target condition. Subjects performed 15 practice trials before performing a block of 20 test trials in each condition. The presentation order of conditions was counterbalanced between subjects.

3.3. Data analysis

When subjects contact the target at its edge, the mechanics of making contact are different: the side instead of the surface of the target decelerates the finger. As we cannot measure this force, we had to exclude such trials. To do so, we calculated the points of force application for each trial from the measured forces and torques. Trials in which these points were within 1.5 mm of the edge of the target (3.4% of all trials) were removed from analysis. Trials in which the MT was more than two standard deviations above or below the mean for that subject and condition were also removed from further analysis. This resulted in removal of approximately 3.8% of the remaining trials. The data of one subject had to be removed from the analysis, because he reached the maximum of the range of the force sensor.

Only the movements to the first target were analysed. Instantaneous velocity and acceleration were computed from position samples of the IRED's. To do so we fit a second order polynomial to 7 position samples (12 ms window) around each position. Based on three parameters of the fit polynomial we can estimate the finger's position, velocity and acceleration at that instant. This is a convenient method for combining data smoothing and differentiation in a single procedure (Smeets, Frens, & Brenner, 2002). The advantage of this method over conventional filtering is that it does not yield overshoots near a sharp change in velocity (such as the impact with the target). This advantage is illustrated in Fig. 3.

The beginning and end of the movement to the first target were based on the tangential velocity. The onset of the movement was defined as the last frame before peak velocity in which the velocity was smaller than that on the preceding frame. The offset was defined as the first frame after peak velocity in which the velocity was smaller than that on the following frame. We could not use a velocity threshold because subjects were not required to (and indeed did not) stop completely at the first target in the two-target condition. This method is insensitive to the impact itself. In Fig. 4 the difference between both methods of determining the onset and offset of the movement are shown. When using an fixed velocity threshold, with longer movement

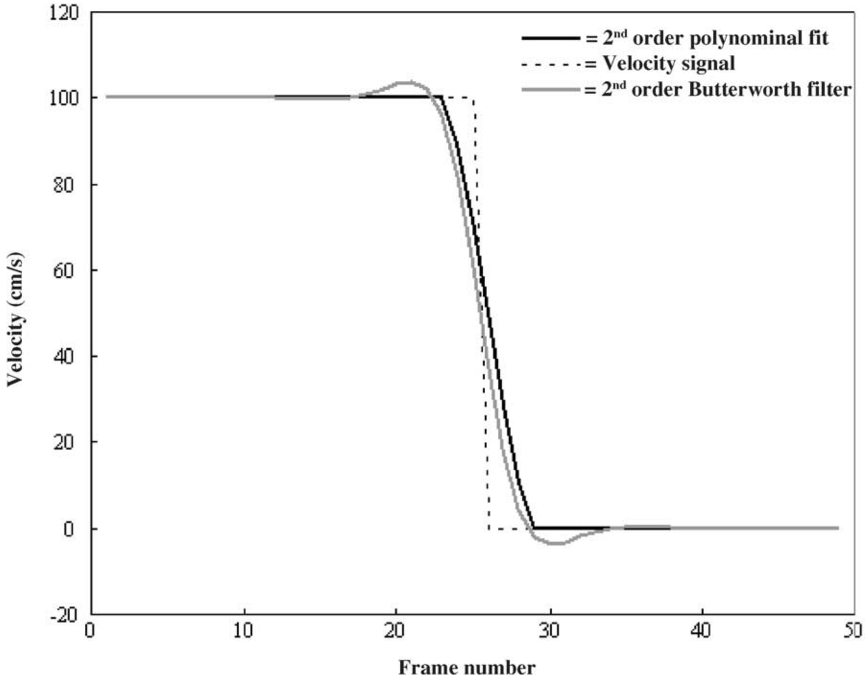

Fig. 3. Comparison between our smoothing for the determination of velocity and the use of a second-order-dual pass Butterworth filter. Using a Butterworth filter (grey line) with a cut-off frequency of 35 Hz induces overshoots near sharp edges in the velocity profile. Using a second order polynomial fit with a 12 ms moving window (black line) does not introduce such overshoots. The dashed line denotes the modelled velocity signal.

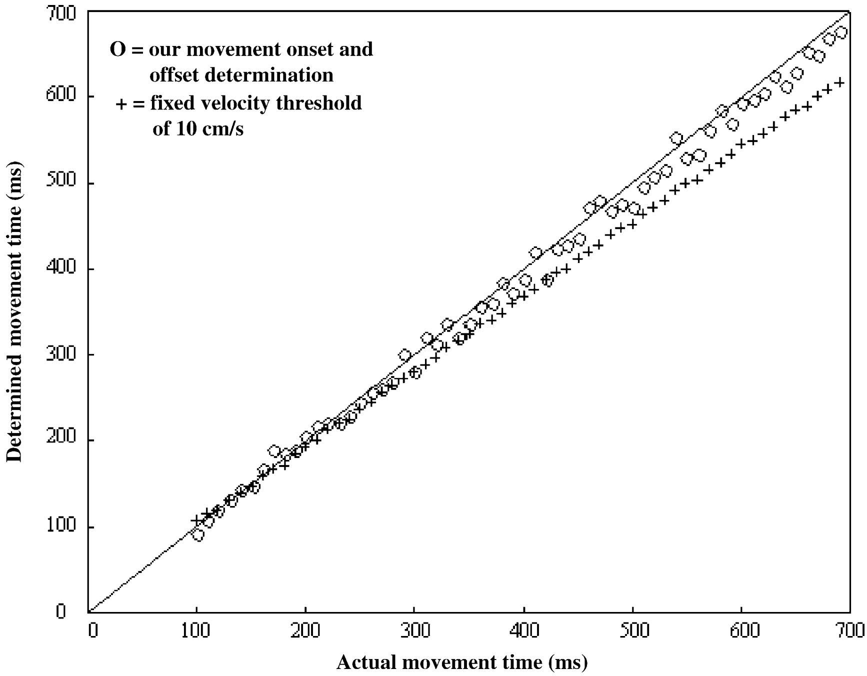

Fig. 4. Comparison between our determination of movement onset and offset (see method section; open circles) and that when a fixed velocity threshold (10 cm/s; crosses) is used. The unity line indicates the actual (simulated) movement time. The modelled trajectories were 10 cm minimum-jerk movements with noise.

durations, the detected movement times deviate more from the actual movement time.

The MT (time between onset and offset of the movement), the travelled horizontal distance and the maximum height of the trajectory of the finger were determined for each trial. Traces of the horizontal impact forces at the first target were averaged as a function of time after being synchronised with respect to the movement offset. Velocity traces were averaged as a function of relative time. This relative time was subsequently multiplied with the average movement time.

A repeated measures ANOVA was used to test the difference between MT, peak velocity and time of peak velocity in the one-target and in the two-target condition.

4. Results

4.1. Movement time

There was a significantly shorter MT in the one-target condition (176 ms) than in the two-target condition (193 ms, Fig. 5A), The 17 ms (8.8%) one-target advantage

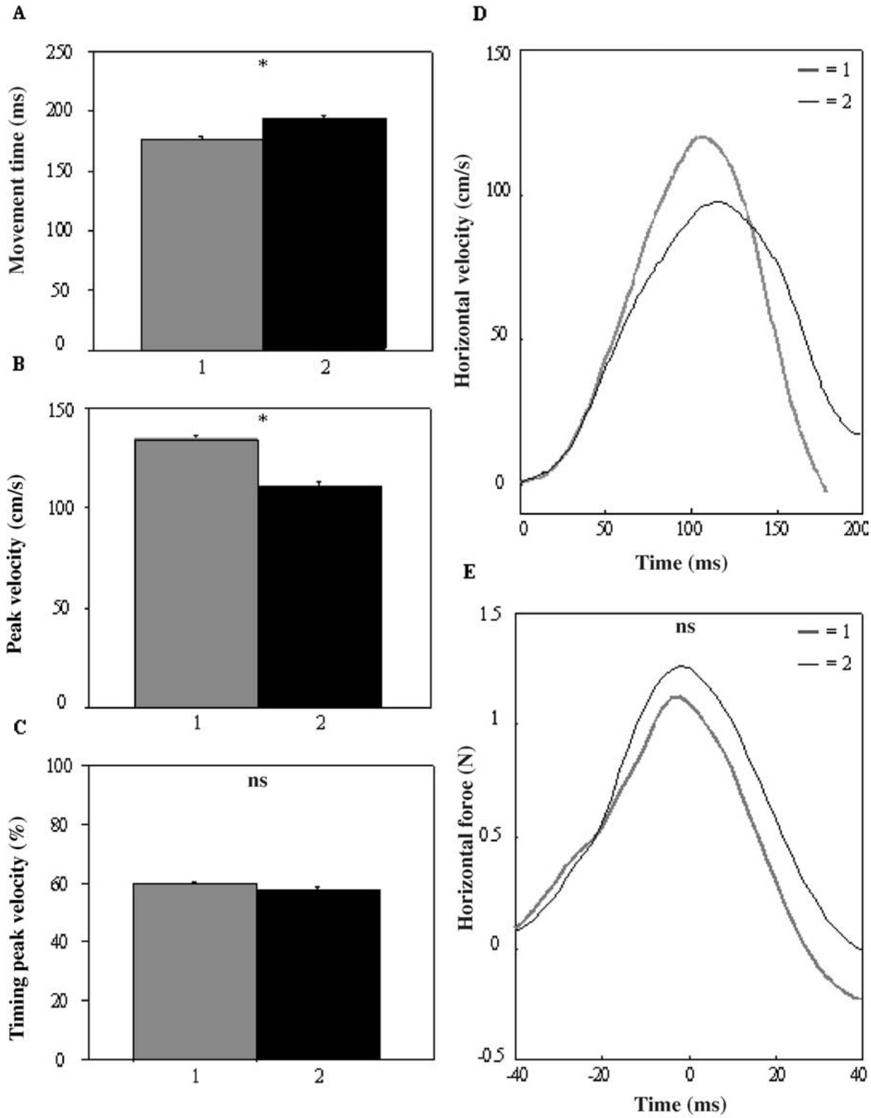

Fig. 5. Mean values of MT (**A**), peak horizontal velocity (**B**) and relative time of peak velocity (**C**) for the one-target condition (grey bars) and the two-target condition (black bars). $* = p < 0.05$. (**D**) The average horizontal velocity as a function of the average time relative to movement onset. (**E**) The horizontal force, averaged relative to the time of the end of the movement for the two conditions. Positive values represent forces applied in the direction of the main movement (leftward). Note that due to the averaging process, the peak of the average velocity traces in (**D**) are slightly lower than the averages of the peak velocities in (**B**).

was similar to values found in other studies (for an overview see Adam et al., 2000), and close to the 10% we assumed in our model calculations.

4.2. Distance

The travelled horizontal distance was 106 mm in both conditions. The maximum height of the trajectory was about 28 mm. These values were not statistically different between conditions.

4.3. Velocity

Peak horizontal velocity was significantly higher for the one-target condition than for the two-target condition (Fig. 5B). The timing of the peak velocity occurred at 60% of the movement time (Fig. 5C) and did not differ between the conditions ($p = 0.18$). Fig. 5D shows the average velocity traces, synchronised at movement onset.

4.4. Force

The horizontal force around movement offset is shown in Fig. 5E. Horizontal and vertical impact forces did not differ between conditions ($Fx = 1.25$ N, $p = 0.12$; $Fz = 3.67$ N, $p = 0.36$). This is inconsistent with the deceleration hypothesis.

5. Discussion

We hypothesised that the one-target advantage could be explained by a difference in deceleration at impact: in the one-target condition we expected deceleration to be larger than in the two-target condition. According to our model for the deceleration hypothesis a larger deceleration at the target (a larger a_p) will give rise to a later timing of the peak velocity. The alternative speed-hypothesis predicts that peak velocity will be higher in the one-target condition than in the two-target condition, and will be reached at the same relative time. Moreover, the final deceleration should be zero for both conditions.

We reproduced the one-target advantage in our experiment. However, we did not find a higher impact force for the one-target condition than for the two-target condition (even a trend in the opposite direction!), which is opposite to the fundamental prediction for the deceleration hypothesis. The peak velocity was significantly higher in the one-target condition than in the two-target condition and was reached earlier in absolute time (see Fig. 5D). Both results are consistent with the speed-hypothesis model. The timing of peak velocity did not differ between the conditions, but peak velocity was not reached at 50% of the movement time as predicted by the speed-hypothesis, but at 60%.

From Fig. 5D it can be seen that there is a difference in final deceleration (the slope of the velocity curve at its end) between the conditions. The final deceleration in the two-target condition is close to zero, while the final deceleration in the one-target condition is much larger. This is what we had predicted, but the reason for this cannot be as assumed for our prediction because the impact force does not show a corresponding effect. The higher final velocity in the two-target condition presumably has a similar effect as the non-zero final deceleration in the one-target condition on the timing of the peak velocity. To account for the combination of less deceleration of the finger at the time of contact and yet a larger impact force in the two-target condition, we have to conclude that the impact force in the two-target condition does not decelerate the finger. Instead it may primarily deform the skin during contact, which is less inconsistent with the high velocity during contact with the first target in the two-target condition.

The timing of peak velocity always seems to follow the prediction of the deceleration hypothesis for the one-target condition: a peak at 60% of the movement time. Therefore we conclude that impact force influences the velocity profile in both conditions. However, the one-target advantage cannot be explained by a *difference* in impact force. Neither a larger impact force nor the kinematic changes that are predicted by the deceleration hypothesis were found experimentally. Thus our hypothesis is rejected, favouring a non-mechanical explanation of the one-target advantage.

Acknowledgements

We thank Jos Adam for his useful suggestions regarding the set up of the experiment. This research was supported by grant MaGW 425-203-03 of the Social Science Research Council of The Netherlands Organization for Scientific Research.

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