The Effect of Movement Time and Movement Distance on the Form of the Force-Time Curve

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Running Head: Force-Time Shape Constancy

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Two models of motor control have emerged recently that predict the accuracy of rapid limb movements based on physical principles as well as some assumptions about characteristics of the muscular impulses driving the limb. Both models, the impulse-variability model (Schmidt, Zelaznik, Hawkins, Frank, and Quinn, 1979) and the symmetric impulse-variability model (Meyer, Smith & Wright, 1982), make an assumption about the form of the force-time curve produced in rapid actions, and along with other mathematical and statistical assumptions both attempt to predict movement outcome as a function of movement distance (A) and movement time (MT). Schmidt et al. (1979) modeled the sinusoidal-like force-time curves as rectangles with some height F and some duration T. To predict distance as a function of force and time (i.e., $D = F \cdot T^2$, where F is force and T is time), they assumed that the shape of the force-time curve must remain constant across changes in A and MT. The meaning of "shape" here is specific. Two force-time curves (with normalized MTs) have the same shape if and only if the amount of force generated at each point in relative time is proportional. For Meyer et al. (1982), they assume in rapid unidimensional aiming responses, the force-time curve has a specific prototypical form which varies as a function of the degree of correlation between a random force parameter and a random time parameter. When the two parameters are uncorrelated, the peak force should occur at about 50% through the MT. When the two parameters are negatively correlated, the peak force should occur before the 50% point, and when the parameters are positively correlated the peak force should occur after the 50% point. However, neither model provided empirical support for the shape assumption stated in each model.

Some studies exist that show the notion of shape-constancy is at least reasonable. Freund and Budingen (1978) have found that the form of rapidly-produced isometric and dynamic force-time curves is similar across a wide range of force requirements. However, it is impossible to determine if the peak in force occurred at the same relative time in each force condition (as the shape constancy assumption requires) because MT was not controlled. In addition, the shape constancy assumption was supported by the fact that the rate of rise of tension was directly related to the amount of force produced, such that the larger the impulse, the steeper the slope (i.e., peak force/time to peak force). Ghez (1979) has shown that the time to peak force is constant across variations in movement distance in rapid forelimb movements in cats, supporting the notion of shape constancy. Here again, MT was not controlled and it cannot be known whether or not the subjects intended to move in the same MT in each distance condition. Therefore, the distinct effect of MT and A on the shape of the force-time curve cannot be discerned from this experiment.

Given the shortcomings of the Freund and Budingen (1978) and Ghez (1979) studies, the main goal of this study was to determine the effect of A and MT on the shape of the force-time curve. Schmidt et al. (1979) and Meyer et al. (1982) both make assumptions abdout the shape of the force-time curve upon which their respective models depend. If shape-constancy is supported, then the impulse variability model will be supported; on the other hand, if the shape of the force-time curve shifts with movement conditions, then Meyer's model would be supported.

Two experiments are reported here, each very similar in methods and procedures. The first experiment examines the effect of movement distance on the shape of the force-time curve, while the second examines the effect of MT on the shape of the force-time curve.

EXPERIMENT 1

Methods

Apparatus

The apparatus consisted of a horizontal aluminum lever 55 cm in length and 5 cm in width, mounted to a 25 cm long vertical steel axle. Ball-bushings supporting the axle were attached to the side of a standard metal desk. The lever was fitted with a D-shaped handle which was connected to the lever via a metal plate and a bracket. A strain gauge detected distortions in the metal plate caused by forces occurring in the horizontal plane. A ceramic one-turn potentiometer was secured to the bottom of the axle to provide position information. Output from the potentiometer and strain gauge were recorded on magnetic tape for later analysis. Movement away from a microswitch activated a millisecond timer. The timer was stopped when a second microswitch (the position of which was determined by the experimental condition) was contacted by the lever. An eight-bank program timer, activated by depressing a telegraph key was used to maintain the intertrial interval between 10-12 sec and to operate a green "Go" light that indicated to the subject when to move.

Subjects

Four right-handed undergraduate students from UCLA (three males and one female) served as subjects for this experiment. They were not paid for their services.

Task

The subject grasped the handle of the lever with the right hand and held the lever at the starting location such that the elbow was flexed 40 degrees with respect to complete extension. With the illumination of the "go" light, the subject moved the lever past a microswitch located 30 deg or 45 deg from the starting location, then moved back through the starting location in 300 msec with a follow-through allowed. The subject was reminded that this was not a "reaction time" task and that the "Go" light only gave a general indication of when to move.

Procedures

Each subject produced 40 trials in each A condition with KR (knowledge of results) about MT given after every trial. The presentation of the A conditions was balanced across subjects so that two subjects began with the 30-deg condition and two subjects began with the 45-deg condition and then alternated on the next set of test trials. The experimenter recorded the total MT from the millisecond timer after each trial.

Data Analysis

The force-time and displacement output were digitized from the magnetic tape at 500 Hz and stored on hard disks using a Minc 11/23 lab computer. With computer software, all trials were synchronized in time based on when the force-time curve significantly departed from the zero-force baseline. Next, all force-time curves were normalized on the basis of time so that the level of force at any given relative time (i.e., at 40% through the accelerative impulse) could be determined. On each trial for each subject the amount of force developed at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% through the accelerative impulse was determined and expressed as a proportion of the peak force developed on that trial. The nine proportions (10% to 90%) for each of the last 20 trials from each A condition were entered into an ANOVA (subjects x A x trials) with repeated measures on the last two factors.

In addition, only the accelerative portion of the force-time curve is considered here due to the nature of the models involved. The impulse-variability model predicts movement outcome for rapid-timing, reversal, and three-dimensional aiming responses, while the symmetric impulse variability model (Meyer et al. 1982) predicts movement outcome for uniplanar aiming responses. For the reversal response not only halts the limb, but drives the limb in the opposite direction.

RESULTS

Timing Error

Reversal Time. The mean time to reversal was approximately 3.5% longer for the 45-deg condition compared to the 30-deg condition (186 ms to 181 ms). However, this difference was not significant, $F(1,3)=3.1, p>.05$. The SD in the time to reversal was similar for both A conditions, being 13.0 ms and 12.5 ms for the 30- and 45-deg conditions respectively. The effect of A was not significant, $F(1,3)=.3\ p>.05$.

Movement Times. The mean MT for the 30-deg condition was about three milliseconds slower than the 45-deg condition (302 ms to 304.8 ms), but the difference was not significant, $F(1,3)=1.1, p>.05$. For MT variability, the 45-deg condition showed about two milliseconds less error than the 30-deg condition (17.3 ms to 19.0 ms). However, this difference was not significant, $F(1,3)=.9, p>.05$.

Spatial Error

The within-subject mean reversal point for the 30- and 45-degree conditions, respectively, were 35.8 and 53.7 deg. This result is not surprising since the instructions were to move past the target microswitches before reversing the limb. The effect of A was significant, $F(1,3)=267.1, p<.05$. In terms of reversal point variability (We), the effect of A appeared to be large with the 45-deg condition showing about 15% greater variability than the 30-deg condition (2.6 to 3.6 deg). The effect of A was significant, $F(1,3)=11.1$, $p<.05$.

Impulse Characteristics

Peak force. Increasing A increased the peak force from .95 kg to 1.40 kg. The effect of A was significant, $F(1,3)=72.3$, $p\leq.05$. The variability in peak force also increased with movement amplitude, (from .14 kg to .17 kg) the difference being significant $F(1,3)=10.9, p<.05$.

Impulse Duration. Since MT was essentially constant no difference was expected in impulse duration (the amount of time the force-time curve was above the zero-force baseline). This appeared to be the case with mean impulse duration increasing about two milliseconds (151.0 to 152.7 ms) as A increased. The effect of A was not significant, $F(1,3,=.3, p>.05$. There was also no effect on the variability in impulse duration, with the 45-deg condition showing less than one millisecond more error than the 30-deg condition (14.9 ms to 14.1 ms). The difference was not significant, $F(1,3)=.4$, $p>.05$.

Shape of the Force-Time Curve

The effect of A on the shape of the force-time curve is shown in Figure 1, where the mean proportion of peak force is shown for both A conditions, plotted by relative time. Both force-time curves seemed to be quite similar in form, reaching peak force at about the same relative time. The effect of A was not significant, $F(1,3)=.01$, $p>.05$. The A x relative time interaction was also not significant, $F(8,24)=.25$, $p>.05$. Therefore, the "shape constancy" assumption of the impulse variability seems to be well-supported by these results, with changes in movement distance having no effect on the shape of the force-time curve.

Insert Figure 1 about here

EXPERIMENT 2

Methods

Many of the methods and procedures in the second experiment are identical to the first, so only the differences between the two experiments will be described here.

Subjects

Four right-handed graduate students at UCLA (three males and 1 female) served as subjects. They were not paid for their services.

Task

For Experiment 2 the subject was asked to make a rapid reversal movement past a microswitch located 30 deg from the starting location, then move back through the starting location, such that the time to the 30-deg microswitch was either 100 or 150 ms.

Procedures

Each subject produced 50 trials in each MT condition with KR about movement time to the 30-deg switch given on each trial. The presentation of the MT conditions was balanced across subjects so that two subjects began with the 100-MT condition and two with the 150-MT condition, and then alternated on the next set of test trials. Only the last 25 trials in each MT condition were used in the statistical analysis.

Results

Timing Error

As it might be expected, the actual reversal time was considerably longer than the goal MT (the time to the switch at 30 deg), due to the time required to stop and reverse the direction of the limb. The mean reversal times were 181.6 ms and 277.4 ms for the 100- and 150-MT conditions respectively. The difference in time-to-reversal was significant, $F(1,3)=124.5, p<.05$, meaning that MT was successfully manipulated.

For the variability in reversal times, the 100-MT condition showed about one-half the timing error than the 150-MT (9.3 ms to 16.9 ms) condition. The effect of MT was significant, $F(1,3)=70.5$, $p<.05$, supporting the predictions of the model relating MT and timing error.

Spatial Error

The subjects reversed the lever past the 30-deg target, reaching an average amplitude of 42.0 and 43.4 deg target, reaching an average amplitude of 42.0 and 43.4 deg respectively, for the 100- and 150-MT conditions. However, the effect of MT was not significant, $F(1,3)=.2$, $p>.05$.

For the variability in the reversal point (i.e., the We), the 100-MT condition showed about a 20% larger We (2.5 to 3.0 deg) than the 150-MT condition. But the effect of ¯T was not significant, F·1,3)=1.7, p>.05.

Impulse Characteristics

Peak force. In terms of peak force, the subjects produced twice the force in the 100-MT condition compared to the 150-MT condition (1.02 kg to .50 kg). The effect of MT was significant, F(1,3)=147.2, p<.05. The same pattern of results was shown for force variability, with the within-subject SD of force nearly doubling as force doubled, (.10 kg to .06 kg). The effect of MT was significant F(1,3)=11.8, p<.05.

Time to peak force. The peak in force occurred earlier in the 100-MT condition compared to the 150-MT condition (109.3 ms and 140.4 ms, respectively). The effect of MT was significant, F(1,3)=12.7, p<.05.

The variability in time-to-peak force was about 30% larger in the 150-MT condition (19.6 ms to 14.7 ms). However, the difference was not significant, $F(1,3)=.9$, $p>.05$.

Impulse duration. The impulse duration appeared to be about 40% longer in the 150-MT condition compared to the 100-MT condition (243.9 ms and 176.7 ms). The effect of MT was significant, $F(1,3)=125.6$, $p<.05$. As expected the variability in impulse duration was related to the impulse duration, with the 150-MT condition showing about 50% more variability than the 100-MT condition. The effect of MT was significant, $F(1,3)=12.8$, $p<.05$.

Shape of the Force-Time Curve

The effect of MT on the shape of the force-time curve is shown in Figure 2, where the mean proportion of peak force is plotted by relative time for both MT conditions.

Both curves seemed to have about the same general form, but the force-time curve for the 150-MT condition appeared to reach peak force earlier in relative time compared to the force-time curve from the 100-MT condition. The effect of MT was not significant, $F(1,3)=.01$, $p>.05$, but the MT x relative time interaction was significant, $F(8,24)=19.2$, $p<.05$. Therefore, the force-time curves here are not proportional when normalized on relative time, resulting in strong support against the notion of shape constancy and the impulse-variability model.

Insert Figure 2 about here

OVERALL DISCUSSION

The present results strongly imply that the "shape constancy" assumption of the impulse-variability model is not valid. Although Experiment 1 showed that A manipulations do not affect the shape of the force-time curve, Experiment 2 showed that changes in MT significantly change the shape of the force-time curve. Therefore, the function relating distance to force and time (i.e., $D = f \cdot t^2$) appears not to hold when MT is varied, seriously violating a major assumption of the impulse variability model. One might argue, however, as Meyer et al. (1982) have, that the shape of the force-time curve might be a function of the correlation between random force and time parameters. If the empirically-determined correlation between force and time can be used to estimate Meyer's parameters, then changes in the correlation between force and time with changes in MT could be the cause of the shape changes with MT noted in Experiment 2. However, the average within-subject correlation between force (the height of the force-time curve) and time (the duration of the force-time curve) was -.49 and -.46 for the 100- and 150-MT conditions, respectively in Experiment 2. The small difference between the two MT conditions is probably too small to account for the shape differences noted in the second experiment. Perhaps the failure of the shape constancy assumption with variations in MT could be the reason the model has failed to predict MT effects in reversal responses (Schmidt, Sherwood, & Zelaznik, 1983).

The force-time curves in the present study (either absolute or relative) appear to be somewhat similar to the prototypical force-time functions predicted by Meyer et al. (1982). In both experiments, the form of the empirical force-time curves appears to be quasi-sinusoidal, as predicted by Meyer et al., but the relationship between the relative time to peak force and the correlation between force and time appear to be incongruous. Although the present force-time curves showed peak forces at about 60% through the impulse, and showed <u>negative</u> correlations between force and time, they are most similar to the prototypical force-time curves predicted by Meyer et al. (1982) with <u>positive</u> correlations between force and time parameters. If the force and time parameters can be estimated by the empirical correlations found here, then Meyer's prototypical force-time functions may not reflect actual force-time curves of reversal responses.

However, the present results do confirm the findings of Freund and Budingen (1978) showing that the time to peak force is directly related to the amount of force produced, such that greater forces require more time to reach peak. The new finding is that the relationship between time to peak force and peak force holds for submaximal voluntary contractions across changes in A and MT. But the present results also suggest that, in terms of relative time, the time to peak force is also directly related to MT such that the slower the MT the earlier the time to peak.

In summary, MT manipulations appear to seriously violate the "shape constancy" assumption of the impulse-variability model, while changes in A left the shape of the force-time curve unaffected. These findings support earlier notions that the impulse-variability model is in need of restructuring before it can become a viable model of rapid limb actions (Sherwood, 1983).

REFERENCES

Freund, H.J. and Budingen, H.J. (1978). The relationship between speed and amplitude of the fastest voluntary contractions of human arm muscles. Experimental Brain Research, 31, 1-12.

Ghez, C. (1979). Contributions of central programs to rapid limb movement in the cat. In H. Asanuma & V.J. Wilson (Eds.) Integration in the nervous system (pp. 304-320). Tokyo: Igaku-Shoin.

Meyer, D.E., Smith, J.E.K., & Wright, C.E. (1982). Models for the speed and accuracy of aimed movement. Psychological Review, 89, 449-482.

Schmidt, R.A., Sherwood, D.E., & Zelaznik, H.N. (1983). Impulse Variability Theory: Recent empirical findings and implications for control of motor behavior. Proceedings of the Psychology of Motor Behavior Symposium, 1, 125-153.

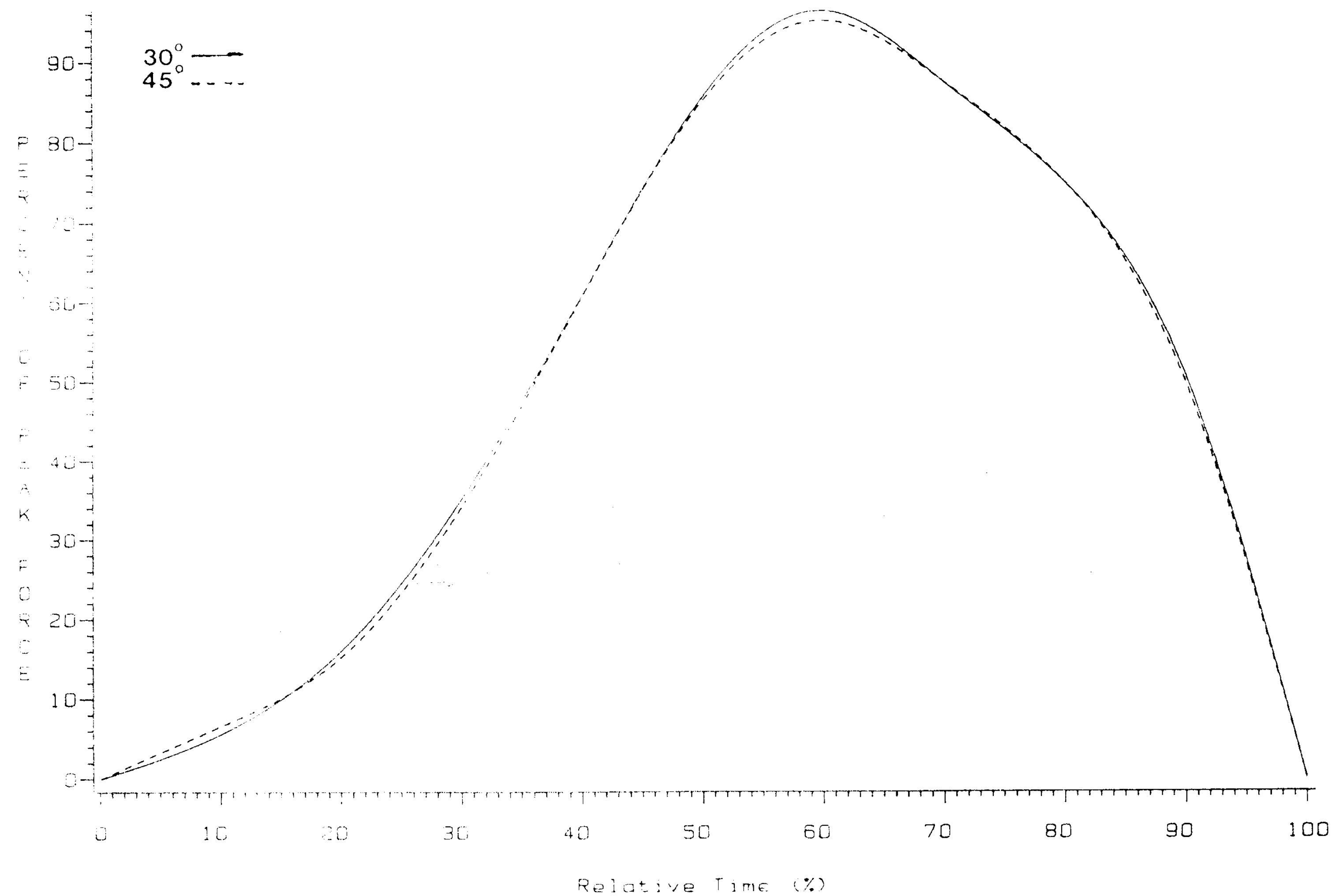
Schmidt, R.A., Zelaznik, H., Hawkins, B., Frank, J.S., & Quinn, J.T., Jr. Motor output variability: A theory for the accuracy of rapid motor acts. Psychological Reviews, 86, 415-451.

Sherwood, D.E. (1984). Impulse characteristics in rapid movement: Implications for the impulse-variability model. Unpublished doctoral dissertation, University of Southern California.

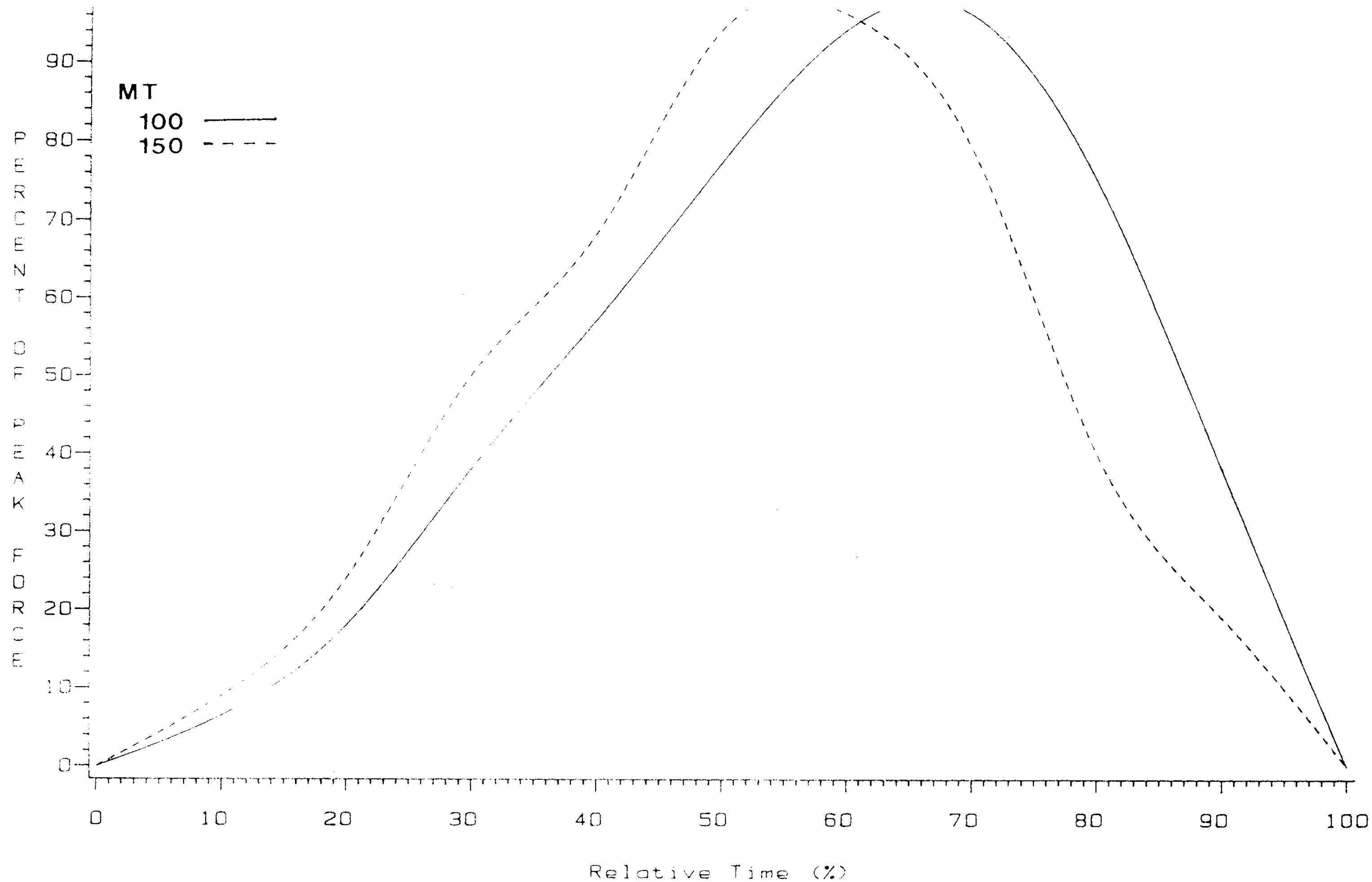
FIGURE CAPTIONS

Figure 1. The effect of movement distance (A) on the shape of the force-time curve (solid line - 30 deg; closed circles - 45 deg)

Figure 2. The effect of movement time (MT) on the shape of the force-time curve (open circles - 100-MT condition; dashed line - 150-MT condition)



30°
45°
OF PEAK FORCE
0
10
20
30
40
50
60
70
80
90
100
Relative Time (%)


MT
100
150
PERCENT OF PEAK FORCE
0
10
20
30
40
50
60
70
80
90
100
Relative Time (%)