Exploitation of elasticity as a biomechanical property in the production of graphic stroke sequences *

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In the present study we report several findings which indicate that subjects exploit elasticity of muscles and tendons as a biomechanical property of the motor system in the execution of graphic stroke sequences. The drawing movements of 15 right-handed subjects were analyzed, who copied a geometrical pattern consisting of four line segments. Three of these segments were connected by an acute and an obtuse angle. A first analysis concerning stroke-direction preferences shows that subjects tended to produce final strokes in preferred movement directions and obeyed an end-state stability constraint. Subsequently, we analyzed the copying movements with respect to (1) pauses at acute and obtuse angles, (2) local deviations in angle size, and (3) size variations of the strokes surrounding the angles. The results reveal a higher incidence of pauses at obtuse than at acute angles. Furthermore, a local sharpening of angles was found which was most pronounced at obtuse angles. Finally, systematic size variations of the strokes surrounding the angles were found. The results are considered to reflect the functional use of elasticity during task performance. It is concluded that biomechanical properties of the motor system significantly influence higher-order preparatory processes involved in multi-trajectory control.

Recent computational models of single-trajectory control are based on assumptions regarding equilibrium points (Bizzi et al. 1984; Feldman 1986; Mussa Ivaldi et al. 1985), potential energy fields (Mussa Ivaldi et al. 1988), optimization principles (Hogan 1984; Flash and Hogan 1985), and difference vectors (Bullock and Grossberg 1989).

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Models of multi-trajectory control, however, are generally based on assumptions regarding syntactical rules and hierarchical programming (Van Galen and Teulings 1983; Rosenbaum et al. 1987; Meulenbroek and Van Galen 1988; Schomaker et al. 1989; Thomassen and Tibosch 1991). Whereas the former type models mainly account for low-level sources of variation such as biomechanical properties of the motor system, the latter type models usually account only for high-level sources of variation such as task demands involved in (or imposed on) the production of complex movement sequences. An interesting question with respect to the relationship between low-level and high-level sources of variation in motor control is whether biomechanical properties of the motor system only influence the dynamics of single-trajectory formation or whether these properties also affect higher-order preparatory processes involved in multi-trajectory formation.

Outside the domain of graphic motor control an example which suggests that biomechanical properties indeed influence the organization of movement sequences has recently been reported by Rosenbaum and Jorgensen (1992). These authors showed that subjects obeyed an end-state stability constraint when grabbing a stick to transport it from one location to another. When subjects grabbed the stick, they generally oriented the hand so that, at the end of the task, the arm occupied a comfortable posture, i.e., a posture that allowed the arm to be at or near the middle of its range of rotation about the shoulder (Rosenbaum et al. 1990). This implied that the subjects grabbed the stick in an uncomfortable posture in order to create the opportunity to finish the task in a comfortable posture. One might argue that subjects exploited biomechanical properties of the motor system in selecting the postures that were realized. The elastic property of muscles, tendons, and joint capsules may be considered a likely candidate for such exploitation. Given that subjects started the task with a comfortable posture in which the arm was near the middle of its functional range of motion (Rosenbaum and Jorgensen 1992), we may assume that, by moving the arm towards the edge of its range of motion before grabbing the stick, the mechanical energy resulting from the spring-like properties of the muscles and stored in an elastic form, may have been used for realizing the subsequent positioning movement. It has been demonstrated that the functional use of elasticity is a typical feature of cyclical movements such as produced in tapping tasks (Guiard 1991). In the graphic domain, elasticity can
similarly be expected to play a role in the production of non-figurative cyclical movements such as scribbling, colouring, and shading movements. The exploitation of this biomechanical property of the motor system might even occur in cursive handwriting which, to a certain extent, can also be regarded as a cyclical activity. Indeed, several handwriting models are based on the assumption that two coupled oscillators which operate in an orthogonal fashion are responsible for the high-frequent, and seemingly periodical, production of upstrokes and downstrokes which constitute cursive Latin script (e.g., Hollerbach 1981; see also Plamondon and Maarse 1989). Empirical evidence has questioned the oscillator description of handwriting control (see e.g., Thomassen and Teulings 1985). However, in the present context it should be noted that the cyclical nature of movements is not a prerequisite for elastic energy to be functionally used in the organization of movement sequences. As the observations by Rosenbaum and Jorgensen (1992) suggest, even in a discrete motor task such as grabbing and repositioning an object, the exploitation of spring-like characteristics of muscles and tendons seems to influence the organization of the involved submovements. The present experiment addresses the latter issue, i.e., the possible role of elasticity of muscles and tendons in the execution of (non-cyclical) graphic stroke sequences.

Recently, we reported an experiment in which we analyzed the sequencing characteristics of subjects' drawing movements produced in a copying task (Thomassen et al. 1992). In the present report, the data of that experiment are subjected to further analyses in the context of the theme which we presented above. The subjects copied many variations of a geometrical pattern consisting of four line segments (see left-hand panel of fig. 1). One of the variations of the pattern concerned its orientation on the drawing surface. Eight different orientations were used which varied in steps of 45 degrees. Our analyses concerned the starting positions, stroke directions, and stroke orders which subjects adopted. We found that movements towards the subject and towards the right were used more frequently at the very end of the copying sequences than at the beginning of the sequences. By assuming that the latter movement directions are more stable and comfortable than other movement directions (see also Goodnow and Levine 1973; Ninio and Lieblich 1976; Van Sommers 1984; Meulenbroek and Thomassen 1991), we concluded that our results demon-
strated that subjects also obeyed an end-state stability constraint in the organization of their copying movements. We considered this as evidence that the end-state stability phenomenon as reported by Rosenbaum and Jorgenson (1992) could be generalized to the graphic domain.

Our earlier findings concerning stroke-direction preferences led us to analyze the data of the experiment of Thomassen et al. (1992) in more detail. We reasoned that if the exploitation of the elastic property of muscles and tendons forms a basic principle underlying the end-state stability phenomenon, this principle would probably also be revealed by other phenomena. For instance, in the case of drawing angles, we expected that it would depend on the angle size whether or not subjects are able to profit from the elastic energy built up during the movement leading up to the angle. We hypothesized that an acute angle would constitute a more favourable condition for this to happen than an obtuse angle because a reversal of movement direction (which is typical of pure cyclical movements) is approximated more in acute than in obtuse angles. To the extent that subjects are unable to profit from the elastic energy built up during a movement for executing a subsequent movement, this is revealed by braking, i.e., a gradual decrease of movement velocity to zero such that the elastic energy can be dissipated by a relaxation or lengthening of the antagonist muscles (Guiard 1991). We reasoned that the latter would be more likely if a discrete movement ending with zero velocity would be followed by a short pause, i.e. a time interval in which no activity could be observed.
For this reason we analyzed the frequency of pauses that occurred at acute and obtuse angles and expected pauses to occur more frequently at obtuse than at acute angles.

An observation which we also considered relevant in this context concerned the local sharpening of angles which we frequently observed in the copying of rectangular patterns. We argued that a local distortion in the form of a sharpening of angles might also be indicative of attempts to create favourable conditions for using the elastic energy built up during a movement for the next movement. We expected that local sharpening of angles would be more pronounced in obtuse than in acute angles because undistorted obtuse angles were considered to be less favourable for elastic energy to be used during the movement following the angle than acute angles.

Finally, we expected that the functional use of elasticity would be reflected by local size adaptations of the movements prior and subsequent to the angles. If subjects exploit the elastic properties of muscles and tendons more in copying acute than in copying obtuse angles, then they are also likely to adapt in an effective manner the size of the movements surrounding the angles in an effective manner. In the case of acute angles, a reversal of movement direction is approximated. Increasing the size of a drawing movement leading up to an acute angle was considered to be effective because then more elastic energy would be built up which could then be used for the movement subsequent to the acute angle. In contrast, increasing the size of a drawing movement leading up to an obtuse angle was considered not to be profitable since the chance of having to move beyond the functional range of motion of the involved limb segments would then increase, and a demanding and time-consuming recalibration of hand and finger position would become likely in this situation. The assumption that more elastic energy would be built up as movement size increases, was based on the general finding in experiments on drawing and handwriting that within a relatively small size range – as being used in the present experiment – subjects scale forces rather than durations to movement size (see e.g., Thomassen and Teulings 1985).
Method

Procedure

Fifteen right-handed adult subjects participated in the experiment. They received credits in the context of course requirements, or were paid Dfl. 15,-. Subjects were seated comfortably in front of a table which could be adjusted in height. A Calcomp 9400 digitizer was used to record pentip displacements at a sampling rate of 100 Hz and spatial accuracy of 0.2 mm. The digitizer was positioned in parallel with the front edge of the writing table. The copying task was performed with a special pen containing an axial pen-force sensor. The pen was attached to the digitizer by means of a thin wire. The digitizer was connected to a VAX workstation from which the experiment was controlled. Before the experiment, subjects performed a few training trials involving 32 patterns consisting of two line segments that formed either an acute or an obtuse angle. The set of training stimuli was completely balanced with respect to angle type and segment size. The sizes of acute and obtuse angles were 45 and 135 degrees, respectively. One line segment of each training stimulus had a length of 0.70 cm, the other segment's length was either 0.35 or 0.70 cm. The training stimuli were presented in eight different orientations varying in steps of 45 degrees. The stimulus patterns were preprinted in a random order in square frames (2.35 cm) on response sheets in three rows of eight frames per sheet. Beneath each row of stimulus frames, a row of response frames of identical size was printed in which subjects had to produce the copying movements. Between trials, subjects had to proceed from left to right within rows, and from top to bottom between rows. Subjects were instructed to copy the stimulus patterns within 3-s trial periods of which the beginning and end were marked by acoustic stimuli. An intertrial period of 5 s was used during which subjects had to move the pentip in the direction of the next response frame without making contact with the drawing surface. Following the subsequent starting stimulus, subjects were required to copy the next stimulus pattern accurately and pay special attention to the size of angles and line segments and to the general orientation of the stimulus pattern within the frames.

The experimental trials followed the same procedure. The stimulus patterns were 256 variations of a prototype pattern consisting of four line segments, two of which were connected to the extremities of a central-segment by an acute and an obtuse angle of 45 and 135 degrees, respectively (see left-hand panel of fig. 1). The fourth line segment was attached to a different location on the central segment. The size of the central segment was 0.70 cm. Variations of the prototype of the stimulus pattern concerned mirroring (two levels); having the fourth segment either in parallel with the segment forming the acute angle or in parallel with the segment forming the obtuse angle (two levels); positioning the fourth line segment on the middle or on one-quarter of the central segment (two levels); varying the sizes of the segments attached to the central segment of the prototype over four levels (all segments 0.35 cm, the parallel segments 0.35 cm and the non-parallel segment 0.7 cm or vice versa, or all segments 0.7 cm); and finally, rotating the stimulus pattern over eight orientations in steps of 45 degrees. An example of a stimulus and response row is given in fig. 2. Arguments for these stimulus variations are discussed in Thomassen et al. (1992).
Data analysis

Pentip displacements were low-pass filtered with a sinusoid filter having a cut-off frequency of 24 Hz and a transition band ranging from 12 to 36 Hz (Teulings and Maarse 1984). The filtering weights were based on Rabiner and Gold (1975). Absolute velocity profiles were displayed together with the corresponding pentip displacements. The pentip displacements were coded in terms of the structural features of the stimulus prototype (see fig. 1). Further details on this coding procedure are given in Thomassen et al. (1992). Minimum-velocity samples were identified interactively, which reflected (1) the beginning and end of pen-down strokes, and (2) the beginning and end of the perpendicular projections on the digitizer of pen-up trajectories. If the velocity minimum corresponding to the end of a stroke did not coincide with the velocity minimum corresponding to the beginning of a subsequent stroke, the time interval between these velocity minima was defined as a pause. A time window of 10 ms was used between subsequent velocity minima. An example of the segmentation procedure is depicted in fig. 3. In the calculation procedures, the time index of an identified minimum-velocity location was estimated more accurately by means of quadratic interpolation of the velocity values of the identified sample and of the two surrounding samples. This procedure increased not only the temporal but also the spatial accuracy of our measurements.

The analyses concerned the orientation and size of the pen-down and pen-up trajectories, the size of the angles at segment borders, and the duration and the distance covered during pauses. Orientation was defined in extracorporal space. With respect to the size of angles between the first three strokes of the patterns, we differentiated between global and local angle sizes. Global angle size was defined by subtracting the directions of two successive strokes. The direction of a stroke was defined by the orientation of the straight line between the initial and final sample of the stroke. Local angle size was defined by subtracting the movement direction 0.5 mm prior to an angle from the movement direction 0.5 mm subsequent to that angle.

The results of the experiment will be presented in four sections. In the first section a general description is given of the sequencing strategies which subjects adopted in the experiment. A few results which were reported earlier in Thomassen et al. (1992) are summarized, and a more detailed description of the subset of the data on which the present analyses were conducted is given. The second section concerns the incidence of pauses at the acute and obtuse angles between the first three strokes of
the patterns. The third section focuses on the local sharpening of the angles between the first three strokes of the patterns. The final section displays the size variations of the strokes surrounding acute and obtuse angles.

Results

**Sequencing characteristics of copying performance**

The central and right-hand panels of fig. 1 depict the two most frequently adopted sequencing strategies. In 84% of the trials (n = 3226), subjects copied the stimulus pattern by producing three connected pen-down strokes, followed by one pen lift and the fourth pen-down stroke. In most cases the fourth pen-down stroke was started at the central segment. If it was not, it always followed the preferred movement direction to the bottom right. Moreover, the data revealed that subjects tended to perform the two parallel segments in immediate succession at the end of the stroke sequences. Since other copying strategies required either more than four strokes or
Fig. 4. Cumulative polar frequency distributions of the copying movements (pen-up trajectories surrounded by dashed circles and pen-down trajectories surrounded by solid circles and indexed with a stroke number corresponding to fig. 1) of the 'acute first' (top) and the 'obtuse first' (bottom) copying sequences. Numbers between two polar plots represent the mean size of the realized angles (degrees) between successive copying segments.

more than one penlift, this finding suggests that a major constraint was economy (see Thomassen et al. 1992). In 16% of the trials, the subjects followed a different strategy, i.e., they produced four strokes and two pen lifts. In these cases, subjects produced significantly more parallels, i.e., two successive strokes in the same direction. The present analyses, however, do not concern frequency analyses of the coded movement directions. Instead, they entail quantitatively determined movement directions, stroke sizes, and angle sizes of the two copying sequences displayed in the central and righthand panel of fig. 1. These sequences are referred to as 'acute first' (41% of all trials) and 'obtuse first' (43% of all trials) in the remaining part of this report.

Fig. 4 depicts cumulative (i.e., pooled across subjects) polar frequency distributions of the realized stroke directions in the 'acute first' sequences (top row, n = 1575) and the 'obtuse first' (bottom row, n = 1651) sequences. In fig. 4, time runs from left to right as indicated by the numbers 1 to 4 which correspond to the stroke numbers indicated in fig. 1. The polar plots surrounded by dashed circles represent the penlift between strokes 3 and 4. The numbers between and immediately below two successive polar plots represent the mean sizes of the angles that were realized between two successive strokes. It should be noted that in the plots of fig. 4 relative frequency distributions are depicted. The figure shows that in both the 'acute first' and the 'obtuse first' sequences, subjects frequently realized righthward and downward movements at the end of the copying sequences (see plots numbered 4). The pen-up movements prior to these final strokes occurred most frequently in top-left directions.
Fig. 4 also demonstrates that the two strokes surrounding the obtuse angles were most frequently produced in downward and rightward direction (plots 2 and 3 in top row and plots 1 and 2 in bottom row). The stroke leading up to the acute angle of the 'acute first' sequences, and the stroke following the acute angle of the 'obtuse first' sequences (plot 1 in top row and plot 3 in bottom row) were more evenly distributed over the orientations in the horizontal plane.

**Pauses at acute and obtuse angles**

A high incidence of pauses was observed at the angles between the first three strokes of the patterns. Subjects paused more often at obtuse than at acute angles ($n = 1856$ and $n = 1139$, respectively), and they paused more often at the second than at the first angle ($n = 1675$ and $n = 1320$, respectively). An inspection of the incidence of pauses per subject revealed that these observations held for all subjects ($n = 15$). Mean pause duration was 158 ms (standard deviation: 84 ms). In the 'acute first' sequences, mean pause duration was 151 ms at the first angle, and 161 ms at the second angle. In the 'obtuse first' sequences, mean pause duration was 146 ms at the first angle, and 169 ms at the second angle. The mean distance covered during the pauses was 0.21 mm (standard deviation: 0.87 mm). In the 'acute first' sequences, the mean distance covered during the pauses was 0.08 mm at the first angle, and 0.26 mm at the second angle. In the 'obtuse first' sequences, the mean distance covered during the pauses was 0.12 mm at the first angle, and 0.33 mm at the second angle. Whereas pause duration and distance covered during the pauses were only slightly different at acute and obtuse angles, the incidence of pauses was clearly higher at obtuse angles.

**Global and local angular deviations**

The median angular deviations, i.e., the median of the differences between instructed and realized angle sizes, per subject are given in table 1. The results are pooled across positions of the angles in the first three strokes of the movement patterns. They are differentiated, however, with respect to angle size (acute versus obtuse angles) and the level of analysis at which these angular deviations were calculated (global versus local). Table 1 shows that acute angles were copied more accurately than obtuse angles by all subjects. On average, acute angles were 1.5 degrees smaller than the instructed angle size (45 degrees). Obtuse angles, however, were 6.3 degrees smaller than the instructed angle size (135 degrees). Locally, these deviations were larger, especially for the obtuse angles. In the immediate surround of the angles, i.e., at a distance of 0.5 mm, acute angles were 3.4 degrees smaller than the instructed angle size, and obtuse angles were 11.8 degrees smaller than the instructed angle size. A one-way ANOVA on these angular deviations, with Angle Size and Level of Analysis as factors, showed a main effect of Angle Size (angular deviations were larger at obtuse than at acute angles, $F(1,14) = 33.00, p < 0.01$), and a main effect Level of Analysis (local angles were more sharpened than global angles, $F(1,14) = 42.41, p < 0.01$). Furthermore, the interaction between Angle Size and Level of Analysis, showing that these local sharpening effects were larger in obtuse than in acute angles, was significant ($F(1,14) = 11.00, p < 0.01$).
Table 1

Median angular deviations in degrees per subject.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Acute</th>
<th></th>
<th>Obtuse</th>
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<td>Local</td>
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**Stroke-size adaptations**

Fig. 5 depicts the relative sizes of the four pen-down strokes of the 'acute first' (solid line) and 'obtuse first' (dashed line) sequences. On average, all strokes were
performed approximately 20% larger in comparison with instructed stroke size. A one-way ANOVA on the mean relative sizes of the pen-down strokes per subject with Sequence Type \((n = 2)\) and Stroke Number \((n = 4)\) as factors revealed a main effect of Sequence Type (overshoots of 22.4% and 19.3% for the 'acute first' and 'obtuse first' sequences, respectively, \(F(1,14) = 11.95, p < 0.01\)), and a main effect of Stroke Number \((F(3,14) = 8.90, p < 0.01)\). As can be seen in fig. 5, the mean size of the fourth stroke was smaller than the mean sizes of the first three strokes. The more interesting finding, however, concerns the significant interaction between Sequence Type and Stroke Number \((F(3,42) = 18.36, p < 0.01)\). In the first two strokes, the strokes leading up to obtuse angles were shorter than the strokes leading up to acute angles. In more general terms, a similar relationship holds for the third pen-down stroke. In the 'acute first' sequences, the third stroke, preceding the pen-up and leading up to an angle of 15 degrees (see fig. 4), was longer than the third stroke of the 'obtuse first' sequences. The latter stroke preceded the pen-up and ended with an angle of 58 degrees (see fig. 4). In the final stroke these differences were absent. To summarize, these results reveal an inverse relationship between the size of an angle and the size of the stroke leading up to that angle.

**Discussion**

The results of this experiment show first of all that subjects obeyed an end-state stability constraint in a large proportion of their copying performances. Earlier, we produced findings indicating that the tendency to reach end-state stability was present in the entire data set (Thomassen et al. 1992). The final strokes were oriented in preferred directions (see Meulenbroek and Thomassen 1991). The present data show, furthermore, that the two strokes subsequent to the initial pen-down strokes were generally oriented in preferred movement directions which means that in the majority of the 'acute first' sequences, subjects were indeed inclined to produce initial strokes in non-preferred or uncomfortable movement directions. The finding that subjects initially adopted uncomfortable movement directions and finished in comfortable movement directions corresponds with the findings of Rosenbaum and Jorgenson (1992). Moreover, the other results of our experiment provide indirect evidence indicating that subjects tended to exploit the elastic properties of muscles and tendons as occasioned at the movement-direction reversals implied in acute angles. Pauses occurred more often at obtuse than at acute angles. Given the long mean duration of the pauses (158 ms), it is reasonable to assume that during these movement interruptions, the
elastic energy built up in the movement prior to the pause is dissipated, e.g., either by the relaxation of antagonist muscle groups or by a minor rearrangement of the involved joints. Such a dissipation of elastic energy built up during a movement towards an angle presumably occurred more often at obtuse than at acute angles. An alternative explanation of the higher incidence of pauses at obtuse than at acute angles is that obtuse angles were more difficult to program than acute angles. Obtuse angles could therefore have required more preparation time. It might also be argued that acute angles are easier to be copied than obtuse angles because of perceptual factors. The latter might be investigated by asking subjects to trace rather than to copy acute and obtuse angles. The results related to the incidence and duration of pauses are therefore open to biomechanical and non-biomechanical interpretations. However, these data are not the only results on which we base our view that subjects attempted to create favourable conditions for the exploitation of elasticity. We observed a local sharpening of angles which was most pronounced at obtuse angles. Finally, we have found that when subjects copied a two-stroke sequence containing an acute angle, which allows subjects more or less to return to the original position from which the angle production started, an increase in the size of the stroke leading up to the angle was observed. This occasioned the building up of elastic energy to be exploited in the production of the stroke following the acute angle. In contrast, when subjects copied a two-stroke sequence containing an obtuse angle, they probably reduced the chance of overextending the involved limb segments by reducing the size of the stroke leading up to the obtuse angle.

In comparison with cyclical activities such as tapping (Guiard 1991) or skiing (Verijken et al., in press), one might argue that in copying, elasticity constitutes a constraining factor in movement production rather than a biomechanical property of the motor system which can be exploited. Moreover, the extent to which muscle elasticity can be exploited may be expected to depend on muscle stiffness which is probably higher in copying than in handwriting as a result of spatial accuracy demands. The high frequency of pauses in the copying of geometrical patterns, as observed in the present experiment, seems to indicate that the potential energy built up during a movement forms indeed an additional biomechanical demand on the control of these movements. However, the present findings concerning a preference to
initiate the ‘acute first’ copying sequences in non-preferred movement directions, a sharpening of obtuse angles, and an effective adaptation of stroke sizes preceding angles, indicate that subjects, generally attempt to select movement sequences and to create conditions locally, which allow them to exploit elasticity. The present results correspond to the findings reported by Thomassen et al. (1992) and Thomassen (1992) who showed that the higher-order effects of the symbolic context and of the opportunity for program repetition interact with the mapping of the biomechanical system upon the geometry of the copying patterns. We conclude that the present findings indicate that elasticity is one of the biomechanical properties of the movement-effector system which significantly influences the organization of discrete graphic movement sequences.

References