Exp Brain Res (2002) 143:515–519
DOI 10.1007/s00221-002-1049-1

RESEARCH NOTE

Theodore E. Milner

Contribution of geometry and joint stiffness to mechanical stability of the human arm

Received: 1 November 2001 / Accepted: 16 January 2002 / Published online: 1 March 2002

Abstract This study investigates the ability to maintain a stable position of the hand when confronted with environmental instability. Subjects were required to hold the hand inside a 0.4-mm square while counteracting the destabilizing effect of a force field, which pushed the hand away from a line in the horizontal plane. The endpoint stiffness of the relaxed arm proved to be a reliable predictor of stability. Subjects were most successful in stabilizing hand position when the direction of the force field was aligned with the direction of greatest endpoint stiffness. They were least successful when the force field was aligned in the orthogonal direction, the direction of least endpoint stiffness. Subjects increased their endpoint stiffness as the strength of the force field was increased, but when the force field was in the direction of least stiffness they eventually failed in stabilizing the hand at the highest force field strength. In contrast, they were as successful in stabilizing the hand at the highest force field strength as at the lowest, when the force field was aligned with the direction of greatest stiffness. With the elbow flexed, endpoint stiffness of the relaxed arm becomes more uniform than with the elbow extended. This was reflected in subjects' performance, which improved considerably compared to the extended elbow posture, as force field strength was increased in the direction of lesser stiffness. The results indicate that posture was more effective than joint stiffness in stabilizing hand position.

Keywords Endpoint stiffness · Posture · Co-contraction · Instability

Introduction

The ability to maintain a stable position of the arm has long been attributed to the spring-like properties of muscles (Asatryan and Feldman 1965). Displacement of a joint by environmental disturbances is immediately resisted by elastic forces produced by muscles. This elastic resistance is frequently quantified in terms of the stiffness of a joint. Joint stiffness has been shown to increase in proportion to joint torque (Cannon and Zahalak 1982; Hunter and Kearney 1982). However, joint stiffness can also be modulated independently of joint torque by co-contracting antagonistic muscle groups (Akazawa et al. 1983; De Serres and Milner 1991; Milner et al. 1995).

In the same way that joint stiffness stabilizes joint position, endpoint stiffness stabilizes hand position. However, the immediate resistance of the arm to displacement does not simply depend on joint stiffness. It also depends on joint angles and limb segment lengths, i.e., the geometry of the arm. Due to this geometric dependence, endpoint stiffness is not uniform, but varies with the direction in which the hand is displaced (Mussa-Ivaldi et al. 1985). Consequently, the arm can be less stable in certain directions than others. The postural stability can be quantitatively represented in the form of an ellipse, constructed from the eigenvalues of the endpoint stiffness matrix. The orientation of the ellipse (direction of maximum stiffness) is determined by the direction of the eigenvector associated with the maximum eigenvalue of the endpoint stiffness matrix (Mussa-Ivaldi et al. 1985). The direction of minimum stiffness, i.e., the direction of least stability, is orthogonal to this direction. If no net endpoint force is exerted by the hand, the endpoint stiffness matrix, K_e, can be related to the joint stiffness matrix, K_j, by the following equation:

$$K_e = \left(J^T\right)^{-1} K_j J^{-1} \tag{1}$$

where the Jacobian, J, is a function of the limb segment lengths and joint angles. It is clear from Eq. (1) that a uniform increase in the stiffness of all muscles would increase the endpoint stiffness in all directions, provided that the arm remained in the same posture. Mussa-Ivaldi et al. (1985) demonstrated such scaling of the endpoint stiffness when subjects were instructed to maintain hand position in the presence of time-varying external disturbances.

T.E. Milner (✉)
School of Kinesiology, Simon Fraser University,
Burnaby, B.C. V5A 1S6, Canada
e-mail: tmilner@sfu.ca
Fax: +1-604-2913040

While this study demonstrated that increased joint stiffness was used to increase the stability of hand position, it did not attempt to determine the relative importance of joint stiffness and geometric factors. Increased joint stiffness, achieved by muscle co-contraction, not only has a high metabolic cost, but could be associated with greater variance in hand position over time. The latter effect is postulated because variation in motor output increases as muscle contraction increases (McAuley et al. 1997). Thus, strategic positioning of the arm to exploit the contribution of geometry to endpoint stiffness, may be more effective than co-contraction, depending on the direction and magnitude of an environmental instability. This study investigated two hypotheses. The first was that increased joint stiffness would not provide adequate stabilization in directions in which stability was low due to geometric factors. The second was that endpoint stiffness would be modulated in proportion to the magnitude of an environmental instability, regardless of the direction of the instability.

Materials and methods

Twelve subjects (eight male and four female) participated in this study. One male subject was left-handed, the rest were right-handed. All subjects performed the task with their dominant arm. All subjects gave informed consent prior to participating in the study. The protocol was approved by the institutional ethics review committee and conformed to the Declaration of Helsinki.

Experimental setup

Subjects were required to stabilize the hand while counteracting a destabilizing force field generated by a two degree-of-freedom serial-link robot manipulandum, which moved in the horizontal plane. The subject's arm was supported against gravity by means of a sling suspended from the ceiling, which cradled the arm near the elbow. The subject grasped a handle located at the end of the outer link of the manipulandum. The handle rotated freely to prevent torque from being applied. The apparatus is described in greater detail by Conditt et al. (1997) and Scheidt et al. (2000). A six degree-of-freedom load cell at the handle measured the force applied by the subject. Optical encoders on the shafts of the motors driving each link, measured shaft angle with a resolution of 0.0275°, permitting x and y handle position to be determined with a resolution exceeding 0.04 mm. Endpoint force and shaft angles were sampled at 1,000 Hz.

The destabilizing force field was implemented as a command to the robot manipulandum to create a force field aligned with either the x- or y-axis, according to Eq. (2).

$$F = \begin{bmatrix} k(x-x_0) \\ 0 \end{bmatrix} \text{ or } F = \begin{bmatrix} 0 \\ k(y-y_0) \end{bmatrix} \quad (2)$$

Here (x, y) is the handle position and (x_0, y_0) is the target position. The force field strength, k, was varied to modify the level of instability in the direction of the force field. Force field strengths were 0, 200, 300, and 400 N/m for male subjects and 0, 100, 150, and 200 N/m for female subjects. There were two target positions, as illustrated in Fig. 1. At the far target, the subject's hand was positioned so that the line joining the handle and center of rotation of the shoulder would be parallel to the y-axis with the elbow angle, θ_e, at 40°. The subject retained the same shoulder angle at the near target, but with greater elbow flexion (θ_e=80°). The situation for the left-handed subject was simply the mirror image of Fig. 1. The shape, orientation, and relative size of the endpoint stiffness ellipses of the relaxed arm at the two target positions shown in Fig. 1 are approximations based on the data of Mussa-Ivaldi et al. (1985).

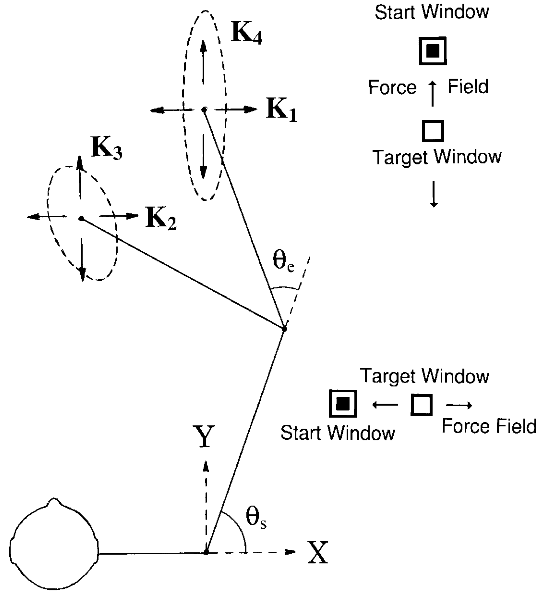

Fig. 1 The orientation of the coordinate system with respect to the subject and the two hand positions are illustrated. The convention used for shoulder angle, θ_s, and elbow angle, θ_e, are also indicated. The K_i (i=1, ..., 4) represent the relative stiffness of the relaxed arm in the directions indicated by the associated arrows, with K_1 being the lowest and K_4 the highest stiffness. The *arrows* also represent the directions of the force field for the two hand positions. The *insets* on the right of the figure illustrate the location of the start window relative to the target window when the force field acted in the y-direction (*top*) and in the x-direction (*bottom*). Note that the direction of the force field changed at the center of the target window, as indicated by the *arrows*. The side of the target window on which the start window appeared was randomly varied from trial to trial, i.e., on half of the trials it was on the opposite side of the target window to that depicted in the figure

Protocol

Subjects began each trial by positioning the hand in a start window, centered 2 cm from the target position. The start window appeared randomly on one side or the other side of the target, i.e., the start window was to the left or right of the target when the force field acted along the x-axis and it was posterior or anterior to the target when the force field acted along the y-axis. Hand position, start window, and target window were displayed as squares on a computer monitor (Fig. 1). Trials were self-initiated, allowing subjects to rest between trials. When the subject moved his/her hand into the start window, the force was gradually ramped up to the value of the force field at that position over a period of 4 s. At the completion of the ramp, the target window appeared and the subject was then given 30 s in which to move and stabilize the hand within the window. Hand position was considered stable as soon as it had been maintained within the target window continuously for 2 s. A trial was classified as successful only if this was achieved prior to expiration of the 30 s time limit. The width of the target window was only 0.4 mm, requiring the subject to remain almost motionless. At the end of the 2-s interval, on successful trials, the force field was removed and a 30-ms shaped force pulse (half-sine wave) with an amplitude of ±10 N was applied to the hand. The force pulse was always oriented along the direction of the force field, but varied randomly in sign (positive or negative) from trial to trial.

Table 1 Chronological sequence of conditions

Position	Group 1		Group 2	
	Strength (N/m)	Orientation[a]	Strength (N/m)	Orientation
Far	0	X	0	X
Far	0	Y	0	Y
Near	0	X	0	X
Near	0	Y	0	Y
Far	200 (100)[b]	X	200 (100)	Y
Far	300 (150)	X	300 (150)	Y
Far	400 (200)	X	400 (200)	Y
Near	200 (100)	X	200 (100)	Y
Near	300 (150)	X	300 (150)	Y
Near	400 (200)	X	400 (200)	Y
Near	200 (100)	Y	200 (100)	X
Near	300 (150)	Y	300 (150)	X
Near	400 (200)	Y	400 (200)	X
Far	200 (100)	Y	200 (100)	X
Far	300 (150)	Y	300 (150)	X
Far	400 (200)	Y	400 (200)	X

[a] Orientation of force field or force pulse
[b] Numbers in brackets refer to gains for female subjects

There were 16 conditions (2 targets × 4 force field strengths × 2 orientations). Subjects performed blocks of eight consecutive trials for a given condition. Each combination of target position and stiffness orientation (i=1, ..., 4) was labeled according to its relative endpoint stiffness magnitude, as illustrated in Fig. 1. Subjects were divided into two groups to reduce possible order effects. Both groups performed the zero force field blocks in the same order. Thereafter, the two groups performed conditions in the opposite order, proceeding either from K_1 to K_4 or vice versa. The order of conditions is listed chronologically in Table 1.

Analysis

The number of successful trials for each condition was scored as a percentage of total attempts. The effects of force field strength and K_i on success score were analyzed using ANOVA. Displacement from the target position at 100 ms following onset of the force pulse was used to assess whether subjects increased endpoint stiffness with force field strength. The 100-ms cutoff was chosen to eliminate the possibility of voluntary intervention. This occurred shortly before displacement reached its peak and represented between 69% and 98% of the peak displacement, depending on the condition.

The displacement produced by a force pulse is determined by the impedance of the arm. Perreault et al. (2001) have shown that the impedance of the arm, when actively maintaining posture, is accurately described in terms of an inertial, viscous, and elastic component, whether arising from voluntary or reflex contributions to muscle activation. The effect of inertia was kept constant by comparing displacements only for the same arm posture and same force pulse direction. Therefore, any difference in displacement amplitude could only have been due to a change in the elastic (stiffness) or viscous (damping) parameter. Both the work of Perreault et al. (2001) and that of Gomi and Osu (1998) showed that the endpoint stiffness of the arm is at least 20–30 times as large as the endpoint damping over a large force range. Using this ratio of stiffness to damping, together with the displacement and velocity measured 100 ms after the onset of the force pulse, the force due to stiffness was estimated to be at least 3–5 times as large as that due to damping.

Linear regression between displacement and force field strength was conducted individually for each position and perturbation direction (each K_i condition). In this way, the geometric dependence of impedance was eliminated as a potential confounding factor. As explained above, the impedance due to stiffness was at least 3–5 times greater than that due to damping. Therefore, any variation in the displacement produced by the force pulse in relation to force field strength could be attributed primarily to a variation in endpoint stiffness. A negative slope indicated that endpoint stiffness increased with force field strength.

Results

Different force field strengths were used for male and female subjects based on pilot studies, which had suggested that female subjects would have more difficulty than male subjects in stabilizing force fields of 300 N/m or greater. However, at a field strength of 200 N/m the success scores were not significantly different between male and female subjects for any combination of position and force field orientation (P>0.3), nor were they different for the zero force field conditions (P>0.1). Therefore, all data for male and female subjects were combined in subsequent analysis.

The effect of K_i on success scores is shown in Fig. 2A. When the force field was oriented along the direction of greatest relative stiffness (K_4) there was essentially no change in the success score with force field strength. Subjects achieved success scores close to 100% for all force field strengths. In contrast, the success score decreased dramatically with force field strength when the force field was oriented along the direction of least relative stiffness (K_1). The success score was already significantly lower than in the no force field conditions when the force field strength was only 100 N/m (P<0.025). As the force field strength was increased to 400 N/m, the mean success score dropped to 5%: in fact, the success score was 0% for six of the eight subjects. The effects of K_i and force field strength on success score were highly significant (P<0.0001), but it is clear that this involved an interaction between K_i and force field strength, which was also highly significant (P<0.0001).

The displacement produced by the force pulse decreased with force field strength, as shown in Fig. 2B, indicating that subjects increased endpoint stiffness as

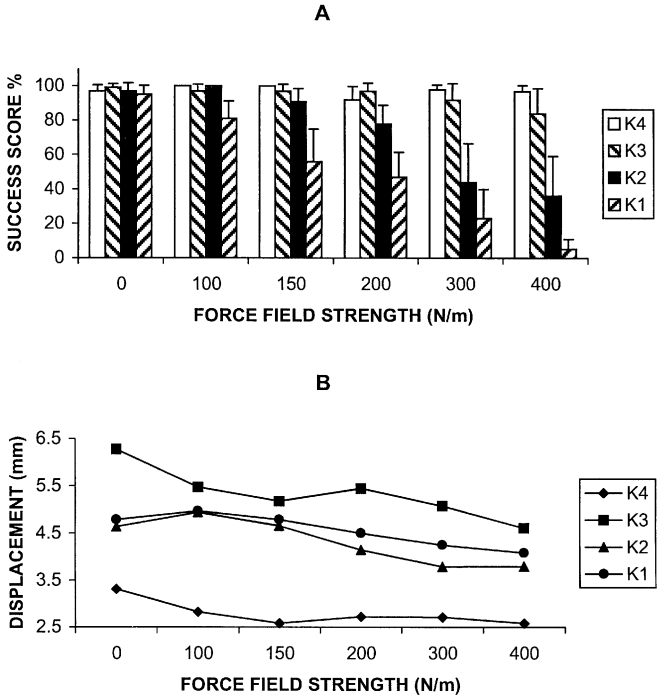

Fig. 2 A The mean and standard deviations of the success scores for the 12 subjects are shown in relation to force field strength. **B** The mean displacements produced by the force pulse for the 12 subjects are shown in relation to force field strength. The K_i (i=1, ..., 4) correspond to the four combinations of force field orientation and hand position shown in Fig. 1. The data for 100 and 150 N/m force field strengths comprise only female subjects (n=4), while the data for 300 and 400 N/m force field strengths comprise only male subjects (n=8)

force field strength increased. Although the slope was significantly less than zero for all K_i conditions (P<0.0001), the data suggested that endpoint stiffness in the K_4 condition stopped decreasing when the force field strength reached 150 N/m. To test this, linear regression was repeated after excluding the data for force field strengths of 0 and 100 N/m. When this was done, the slope was no longer significantly different from zero for K_4 (P>0.6), although it remained significantly less than zero for all other conditions (P<0.0001).

Discussion

The importance of geometric factors in providing stability of hand position is clearly demonstrated by the results of this study. As the strength of the destabilizing force field increased, subjects' ability to maintain a precise position of the hand progressively deteriorated except in the K_4 condition. Because the elbow was extended at this hand position, endpoint stiffness was relatively high in the anterior-posterior direction, the direction of the destabilizing field. In this condition, there was no increase in endpoint stiffness for field strengths above 150 N/m, indicating that subjects were able to stabilize the hand without the need to increase joint stiffness. In contrast, endpoint stiffness was greatly diminished in the orthogonal direction (K_1) and this corresponded to the greatest drop in success score as force field strength increased. At the highest force field strength, the success score dropped to zero for most subjects. It is, therefore, clear that subjects were not able to compensate for the low endpoint stiffness in this direction by increasing their joint stiffness.

The increase in endpoint stiffness in response to increased force field strength could only have been achieved by an increase in joint stiffness since geometric factors were invariant for a given K_i condition. That increase in joint stiffness was most likely due to increased muscle co-contraction. Unfortunately, it was not possible to quantify muscle activation because the electrical equipment interfered with EMG recording whenever the robot manipulandum was in operation. Without EMG records it is not possible to rule out the possibility that the increase in stiffness was due to an increase in myotatic reflex gain without a concomitant increase in muscle co-contraction. However, this would have been extremely unlikely. First, subjects were acutely aware of an increase in muscular effort as the force field strength was increased, particularly for the condition of lowest endpoint stiffness, K_1. Second, our previous investigations on stabilization of single joint posture demonstrated a graduated increase in agonist/antagonist co-contraction with the level of destabilization, which is accompanied by an increase in stretch reflex gain (Akazawa et al. 1983; DeSerres and Milner 1991; Milner et al. 1995).

Accepting that subjects increased endpoint stiffness by muscle co-contraction and an accompanying increase in stretch reflex gain, there are several possible explanations as to why they were unable to compensate for the destabilizing effect of the force field as its strength increased. First, the force field gain may have exceeded the stiffness that could be achieved by co-contraction. We have previously shown that when antagonistic muscle groups are simultaneously active their activation is limited to less than 50% of maximum (Milner et al. 1995). Second, the ability to remain motionless may have deteriorated as co-contraction increased due to increased variability in commands to the muscles or increased tremor (McAuley et al. 1997).

The contribution of elbow flexion to stability was evident from the consistently higher success scores for condition K_2 than K_1 as force field strength was increased. Furthermore, there was less disparity between the success scores in the directions of minimum and maximum stiffness for the posture with greater elbow flexion. This can be attributed to more uniform endpoint stiffness than in the extended posture. In practical terms, these findings indicate that elbow flexion and body orientation can be used effectively to counteract environmental instability. If destabilizing forces are confined to a narrow range of directions the body can be oriented to align the hand and shoulder with the central direction of the environmental instability. By extending the elbow, maximum stability can be achieved. If, on the other hand, destabilizing forces are distributed over a broad range of directions or if their direction cannot be predicted, stabilization can be optimized with a more flexed elbow posture.

Acknowledgements The experiments were conducted in the laboratory of Dr. Sandro Mussa-Ivaldi at the Rehabilitation Institute of Chicago. This work was supported by the Natural Sciences and Engineering Research Council of Canada and by NINDS grant NS-35673.

References

Akazawa K, Milner TE, Stein RB (1983) Modulation of reflex EMG and stiffness in response to stretch of human finger muscle. J Neurophysiol 49:16–27

Asatryan DG, Feldman AG (1965) Functional tuning of the nervous system with control of movement or maintenance of a steady posture. I. Mechanographic analysis of the work of the joint or execution of a postural task (English translation). Biofizika 10:925–935

Cannon SC, Zahalak GI (1982) The mechanical behavior of active human skeletal muscle in small oscillations. J Biomech 15: 111–121

Conditt MA, Gandolfo F, Mussa-Ivaldi FA (1997) The motor system does not learn the dynamics of the arm by rote memorization of past experience. J Neurophysiol 78:554–560

De Serres SJ, Milner TE (1991) Wrist muscle activation patterns and stiffness associated with stable and unstable mechanical loads. Exp Brain Res 86:451–458

Gomi H, Osu R (1998) Task-dependent viscoelasticity of human multijoint arm and its spatial characteristics for interaction with environments. J Neurosci 18:8965–8978

Hunter IW, Kearney RE (1982) Dynamics of human ankle stiffness: variation with mean ankle torque. J Biomech 15:747–752

McAuley JH, Rothwell JC, Marsden CD (1997) Frequency peaks of tremor, muscle vibration and electromyographic activity at 10 Hz, 20 Hz and 40 Hz during human finger muscle contraction may reflect rhythmicities of central neural firing. Exp Brain Res 114:525–541

Milner TE, Cloutier C, Leger AB, Franklin DW (1995) Inability to activate muscles maximally during cocontraction and the effect on joint stiffness. Exp Brain Res 107:293–305

Mussa Ivaldi FA, Hogan N, Bizzi E (1985) Neural, mechanical and geometric factors subserving arm posture in humans. J Neurosci 5:2732–2743

Perreault EJ, Kirsch RF, Crago PE (2001) Effects of voluntary force generation on the elastic components of endpoint stiffness. Exp Brain Res 141:312–323

Scheidt RA, Reinkensmeyer DJ, Conditt MA, Rymer WZ, Mussa-Ivaldi FA (2000) Persistence of motor adaptation during constrained, multi-joint, arm movements. J Neurophysiol 84:853–862