ELSEVIER

Human Movement Science 18 (1999) 87–102

HUMAN MOVEMENT SCIENCE

Postural constraints modify the organization of grasping movements

Christophe Bourdin [a,*], Normand Teasdale [b], Vincent Nougier [a], Chantal Bard [b], Michelle Fleury [b]

[a] *UFRAPS, UPR-ES 597, Université Joseph Fourier, Grenoble, France*

[b] *Faculté de médecine, Département de médecine sociale et préventive, Division de Kinésiologie, Université Laval, Québec, Canada*

Abstract

Reaching and grasping movements have been studied mostly in seated contexts. There are several tasks, however, that also impose specific postural constraints that may affect the organization of these movements. For example, in rock climbing, a successful grasp is conditional of an accurate static and dynamic postural control. The purpose of our study was to analyze if postural constraints, imposed by rock climbing, would mask speed–accuracy tradeoff normally observed in pointing and grasping movements. More specifically, it was predicted that climbers, in order to reduce the duration of the presumably less stable tripodal phase, would shorten the duration of their reachings whatever the size of the hold. This time reduction would be incongruous with the longer end-phase control observed in seated conditions when precision requirements increase. Seven expert rock climbers performed grasping movements in two different postural conditions (easy and complex) towards holds of various depths (0.8, 2 and 5 cm). As expected, the hold depth (precision requirements) did not influence the organization of movements until contact with the hold. More specifically, movement duration and velocity–time profiles of the reachings were not affected by the accuracy requirements but were shortened by an increased postural difficulty. The duration of

---

[*] Corresponding author. Address: UMR CNRS “Mouvement & Perception”, Faculte des Sciences du Sport, Universite de la Mediterranee, CP 910, 163 avenue de Luminy, F-13288 Marseille Cedex 09 France. Tel.: +33 4 91 17 22 78; fax: +33 4 91 17 22 52; e-mail: bourdin@laps.univ-mrs.fr

PII: S 0 1 6 7 - 9 4 5 7 (9 8) 0 0 0 3 6 - 0

force adjustments once a contact with the hold was established increased with a decreased target size and were not affected by the postural complexity. The present findings suggest a hierarchical processing of postural constraints and precision constraints.

PsycINFO classification: 2300; 2560

Keywords: Kinematics; Kinetics; Grasping movements; Postural constraints; Target size

1. Introduction

Most of our every day life actions are directed to grasp objects located in the world around us. These prehensive movements are generally described in two phases (Weir, MacKenzie, Marteniuk, Cargoe & Frazer, 1991a and Weir, MacKenzie, Marteniuk & Cargoe, 1991b; MacKenzie & Iberall, 1994): (a) up to object contact, called the free-motion phase, which is controlled by the visual information, and (b) after contact with the target, when subjects apply functional effective forces (called the finger–object interaction phase), which are controlled by the integration of the visual information and the sensory information regarding object features once contact is made. The extreme variability found in the shape, size, texture, and other intrinsic and extrinsic characteristics [1] of targets require a precise adaptation of the act of prehension. For example, the problem of how the size of the target to be grasped influence the free-motion phase has been frequently addressed. In general, it has been observed that, in accordance with Fitts' law (Fitts, 1954), small object surfaces yield an increased precision requirements for finger positioning and then a longer free-motion phase (Bootsma, Marteniuk, MacKenzie & Zaal, 1994; Bootsma & Van Wieringen, 1992; Castiello, Bennett & Stelmach, 1993; Gentilucci et al., 1991; Jakobson & Goodale, 1991; Marteniuk, Leavitt, MacKenzie & Athenes, 1990; Zaal & Bootsma, 1993).

Other authors have also studied the organization of the finger–object interaction phase. By varying the object weight or its texture, Weir et al. (1991a, b) showed that it is only once contact is made with the object that the

---

[1] As defined by MacKenzie and Iberall (1994), extrinsic object properties referred to egocentric spatial properties such as distance, orientation, direction and velocity of object motion with respect to the body. Intrinsic object properties are identity constituents such as size and shape.

movements differ, with an increase in the time spent in contact with the target prior to lift-off as object weight increases or becomes more slippery. Johansson and Westling (1984) have provided conclusive evidence that we modulate the amount of grip force that we apply to objects of different weight or surface textures to avoid slips.

Movement intentions (i.e., the goal of the movement) also affect prehension movements. Indeed, skilled movements of the hands and fingers occur in a variety of contexts. For example, when subjects had knowledge of the task objectives (place versus throw), Marteniuk, MacKenzie, Jeannerod, Athenes and Dugas (1987) showed a change in the length of the deceleration phase of the transport component of the free-motion phase. The deceleration phase duration increased when subjects were required to take and place the object rather than throw it. The control of posture could also represent another potentially important constraint for the reaching and grasping movements. If we consider the grasping activity in a broader context, it seems essential not only to produce precise and well-controlled reaching and grasping movements, but also to coordinate these activities with the postural activity (MacKenzie & Marteniuk, 1985). This suggestion is in line with that of Biguer, Prablanc and Jeannerod (1984) that a skilled reaching movement is not only a system comprising muscles of the arm, the head and eyes but also includes postural muscles. Indeed, in most complex multi-joint actions, such as grasping an object while standing, the behavior includes a postural component necessary to counteract the perturbation created by the focal movement (Massion, 1992; Gahéry & Massion, 1981; Bouisset & Zattara, 1981). For some activities, this postural component represents an essential requirement. For example, in rock climbing, the grasping activity requires accurate and powerful reaching and grasping movements. But, unlike grasping movements performed in a seated position, the hand grip is not the goal per se. Rather, it is the postural stability that primarily determines the success or the failure of the task. This raises the question of the generalization of previous results on the organization of grasping movements obtained with seated subjects performing grasping movements in a complex postural environment. The purpose of this study was to examine how high postural constraints modify the kinetic and kinematic organization of grasping movements towards targets of various depths.

Quaine, Martin and Blanchi (1997) showed that, when climbers are in an inclined position (difficult posture), the hand served the purpose of stabilizing the posture and counteracting the backward instability. Hence, when a grasping movement is initiated, only one hand can play this postural function during the free-motion phase, leading the climbers to reduce significantly the duration of the free-motion phase. To our mind, this time reduction is incompatible with the increased end-phase control normally observed when precision requirements are high (Bootsma et al., 1994; Bootsma & Van Wieringen, 1992; Castiello et al., 1993; Gentilucci et al., 1991; Jakobson & Goodale, 1991; Marteniuk et al., 1990; Zaal & Bootsma, 1993). In the present experiment, it is hypothesized that postural constraints rather than hold depth (and hence terminal accuracy constraints) will affect the movement up to contact in such a way that a more difficult posture will yield a faster transport phase. On the other hand, once the quadrupedal posture is attained, grasping adjustments associated with the hold difficulty will be observed. Such an organization would suggest that postural constraints can be hierarchically more important than the grasping constraints.

2. Methods

2.1. Subjects

Seven right-handed adults, aged 19–35 (mean age = 23.8 years, height range = 1.75–1.86 m) participated in the study on a voluntary basis. They all signed an informed consent according to university protocols. They were not aware of the purpose of the experiment. All were climbers with at least two years of experience (level of expertise varied from 6b to 6c) [2].

2.2. Apparatus

The apparatus consisted of six climbing holds (two foot holds and four hand holds) fixed on a wall (see Fig. 1). The two foot holds were set 24 cm back from the four hand holds frontal plane, to create an inclination of 10°.

The four hand holds were equipped with strain gauges to measure the vertical component of the forces applied by the climbers. The force signals were sampled at a frequency of 200 Hz (12-bit A/D conversion). An opto-

---

[2] Climbing grades range from 3 to 8, with each grade subdivided into a, b, c. The grades represent the difficulty of the climbing paths. Theoretically, this scale has no upper limit. Currently, the highest rating is 8c. The climber's expertise is defined as the grade of the most difficult path he is able to perform.

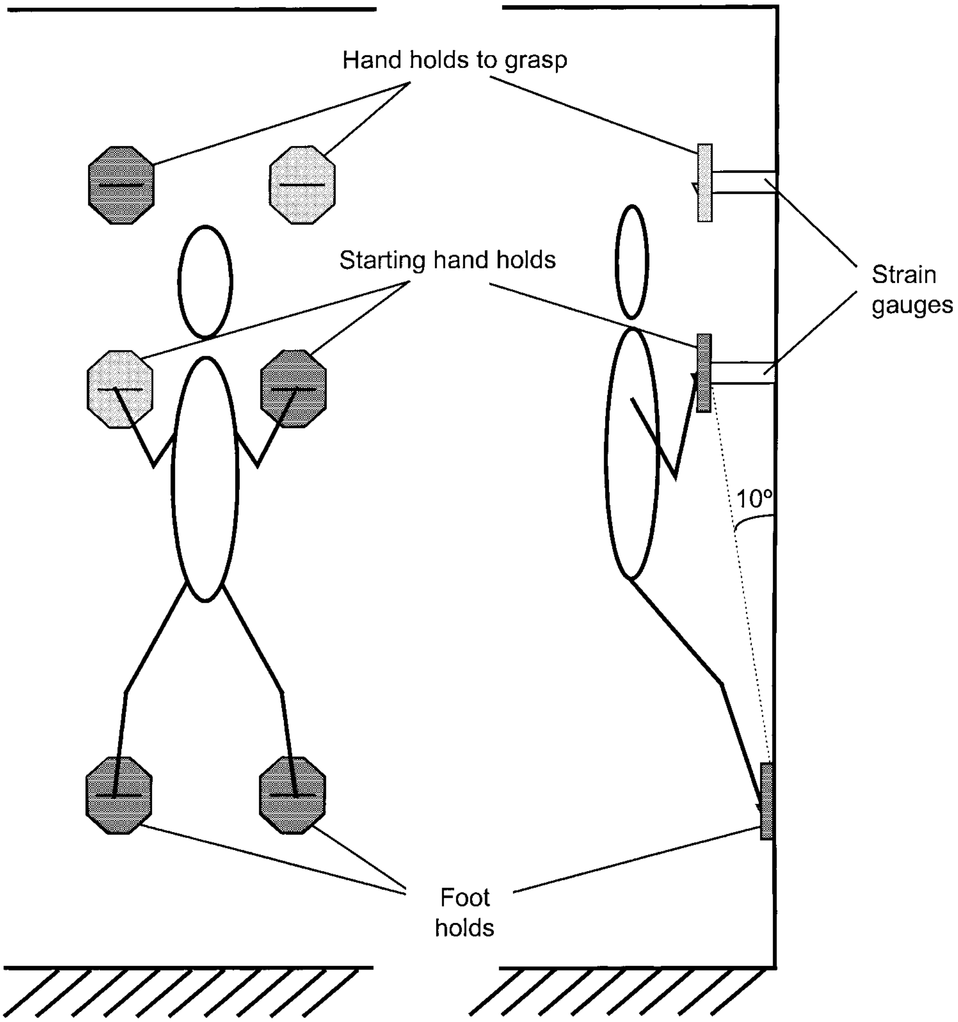

Fig. 1. Illustration of the 10° inclined experimental set-up. The climber is represented in the starting position. Strain gauges recorded vertical forces applied on the four hand holds. The black hand holds did not vary during the experiment, whereas the grey hand holds varied in depth during the experimental session. The Selspot II system is not represented in this figure.

electronic three-camera system (Selspot II) facilitated the 3-D recording of the kinematics of the right hand. An InfraRed Emitting Diode (IRED) was placed on the metacarpophalangeal joint of the middle finger. The position coordinates of the IRED were sampled at 200 Hz for a period of 3 s per trial.

The four hand holds were composed of two starting hand holds (right and left) and two hand holds to grasp (right and left), separated vertically by 35 cm. The holds to grasp were always in the prehension space. All holds were 7 cm wide. The size of the holds only differed in their depth, so that the climbers always used the same four fingers to grasp the various holds (the thumb was not used). The two foot holds, the right-hand starting hold and the left-hand hold to grasp, remained identical during the experiment (depth: 0.8 cm).

As the hands served a postural function (Quaine et al., 1997), the depth of the left starting hand hold was varied to impose specific postural constraints to the climbers. A small left starting hold created a more difficult posture (complex condition) by preventing the climbers from applying large forces. Conversely, a large left starting hand hold allowed the climbers to stabilize their posture more easily (easy condition). This difference in the postural condition was confirmed qualitatively by all the climbers. The depth of the right-hand hold to grasp was also changed during the experiment. Three different depths (0.8 cm: small; 2 cm: medium; and 5 cm: large) were chosen to vary the area available to grasp the hold and consequently the precision requirements of the grasping movements (Bootsma et al., 1994).

2.3. Procedure

When subjects were stabilized in the quadrupedal position, representing the starting position for each trial, the experimenter gave them a verbal signal to move. Subjects were required to perform a right grasping movement followed by a left grasping movement. Climbers were encouraged to perform their grasping movements at their preferred speed. After each trial, subjects came down from the climbing wall. The inter-trial delay was 30 s. The two postural conditions (easy and complex) and the three hold sizes (small, medium, and large) represented six experimental conditions. Subjects performed 10 trials per condition for a total of 60 trials. The postural condition and the hold size were changed every five trials, in a randomized manner.

2.4. Data analysis

Kinetic and kinematic data were smoothed with a Butterworth second order filter with dual pass to remove any phase shift (10 Hz cutoff frequency). Position signals from the IRED were then differentiated twice (finite difference technique) in order to obtain velocity and acceleration–

time profiles. The resultant velocity for a point in time was then calculated by squaring each of the x, y, and z velocities, summing them, and taking the square root of the sum (resultant acceleration was obtained with a similar process).

Compared to single grasping movements, the release of the hold in rock climbing (starting movement of the fingers) was always preceded by preparatory hand movements. These preparatory movements facilitated the release of the hold and were characterized by upward movements of the hand (wrist flexion). To account for this particular organization, we distinguished the preparatory phase and the free-motion phase. The preparatory phase was defined as the time interval between the first movement of the hand and the release of the hold. The free motion phase was defined as the time interval during which the forces on the hold were at 0 N.

The following dependent measures were derived from the kinematic data of the right hand movement: duration of the preparatory phase (ms); peak resultant velocity (cm/s); time to peak velocity (ms) (from the onset of the movement to peak velocity); peak acceleration and deceleration (cm/s^2); and time to peak acceleration and peak deceleration (ms) (from the onset of the movement to peak acceleration and deceleration).

The kinetic data were used to derive the following dependent measures for the right and left hands: free-motion phase duration (ms); peak grasping force (N) (for the finger–object interaction phase, defined as the maximum force attained after contact with the hold); and time to peak grasping force (ms) (from contact with the hold to peak grasping force).

2.5. Statistical analysis

Because the right hand could be considered as the leading hand, results are reported with respect to the chronological behavior of the right hand. Kinetic and kinematic data recorded for the right hand were submitted to 2 Postures (easy and complex) × 3 Holds (large, medium and small) analyses of variance (ANOVA) with repeated measures on all factors.

Kinetic data for the left hand were analyzed using a one-way ANOVA. As the left-hand hold to grasp remained constant during the experiment, only the hold size of the right hand varied for the left grasping movement. Variations in the right hold, which represented the anchoring point for the left movement, were a postural constraint and not a precision constraint for the left hand movement.

3. Results

Table 1 includes a summary of all kinematics and kinetics dependent measures for the right-hand movement, as a function of hold depth and postural condition.

3.1. Right-hand movement

3.1.1. Movement up to contact

The movement up to contact with the hold can be described by analyzing both kinetic and kinematic data. We previously noted that kinematic data for the movement up to contact included preparatory hand movements preced-

Table 1
Means (and standard deviations) for selected dependent measures for the right hand, as a function of posture and hold depth (cm)

Dependent measures	Easy posture			Complex posture		
	5	2.5	0.8	5	2.5	0.8
Kinematic data						
Preparatory phase duration (ms)	167.7	187.3	174.7	177.5	201.5	200.5
	38	19	32	33	34	34
Peak Velocity (cm/s)	126.9	121.2	121.9	144.3	136.7	134.4
	21	15	18	25	23	20
Time to peak velocity (ms)	271.5	281.9	269.8	275.9	289	287.6
	51	34	27	44	47	40
Velocity at contact (cm/s)	12.3	13.3	13.3	20.2	17.3	16.2
	3.3	2.2	2.6	7.8	6.6	4.7
Peak acceleration (cm/s^2)	923.4	891.9	900.8	1063.5	1036.2	1012.4
	179	213	184	177	183	196
Time to peak acceleration (ms/s)	165.1	173.2	160.3	187.8	199.7	204
	38	37	36	46	37	39
Peak deceleration (cm/s^2)	−826	−799.8	−779.9	−1174	−1170.4	−1114.2
	203	172	203	409	397	320
Time to peak deceleration (ms)	409	399.7	390.4	383.5	390	388.9
	43	39	46	66	60	55
Kinetic data						
Free-motion phase duration (ms)	411.2	407.5	408	323.4	325.3	329.1
	60	61	58	57	65	50
Peak force (N)	221.3	198.5	172.2	221.1	206.5	186.6
	68	38	28	52	37	24
Time to peak force (ms)	584.6	691.5	943.7	544.5	734.9	890.8
	156	184	344	122	172	235

ing the release of the starting hold. The ANOVA results from the preparatory phase showed a significant effect of Posture ($F(1, 6) = 41.7$, $p < 0.001$). When the climbers were in the complex posture, the right-hand preparatory phase duration was longer than when subjects were in the easy posture (194 vs. 176 ms). All other effects were not significant (all $p > 0.05$). In the same way, the ANOVA on the free-motion phase duration (kinetic data excluding the preparatory hand movements) showed a main effect of Posture on the free-motion phase duration ($F(1, 6) = 34.36, p < 0.01$). The duration of the right free-motion phase was longer when the posture was easy than when it was complex (408 vs. 325 ms). All other effects were not significant (all $p > 0.05$), suggesting that the size of the hold did not influence the duration of the free-motion phase. Both results suggest that only posture influences the duration of the movement up to contact with the hold. This also shows that, contrary to previous studies that had no postural constraints (Marteniuk et al., 1987; Bootsma et al., 1994), changes in hold depth (i.e., terminal accuracy constraints) do not induce variations of the duration of the movement until contact with the target.

Kinematics of the right hand served to describe more precisely the organization and the control of the grasping movement up to contact, in relation to the depth of the hold and the postural constraints. The ANOVA on the time to peak velocity showed no significant effect. This means that, whatever the conditions, peak velocity always occurred at the same moment (on average, 278 ms after onset of movement) (see Fig. 2). It suggests that the

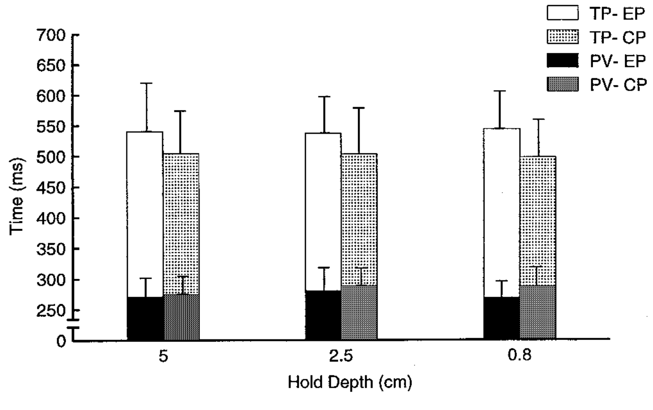

Fig. 2. Mean transport phase durations (TP) and time to peak velocity (PV) for the different conditions of posture (Easy Posture: EP and Complex Posture: CP) and object depths (5, 2.5 and 0.8 cm).

duration of the acceleration phase remains constant whatever the conditions, even when a complex posture induced a shorter movement time.

To examine the effect of the postural constraint on the movement organization, we computed the ratio of the acceleration phase duration (from onset of the free-motion phase until peak velocity) divided by the deceleration phase duration (from peak velocity until end of movement). The ratios obtained for the different conditions of posture and hold size were submitted to a 2 Postures (easy and complex) × 3 Holds (large, medium and small) ANOVA. Results show a main effect of Posture ($F(1, 6) = 12.07, p < 0.01$). The ratio was lower when the posture was easy than when it was complex, showing a greater asymmetry (longer acceleration phase and shorter deceleration phase) for the complex posture than for the easy one (see Table 2).

The peak velocity was significantly affected by the Posture ($F(1, 6) = 31.98$, $p < 0.01$). The maximum velocity was greater when the posture was complex than when it was easy (138.5 vs. 123.3 cm/s). For the peak acceleration, the ANOVA yielded a main effect of Posture on the maximum acceleration ($F(1, 6) = 24.52$, $p < 0.01$). The peak acceleration was greater when climbers were in a complex posture than when they were in an easy posture (1037 vs. 905 cm/s^2). Moreover, the peak acceleration occurred later for the complex than for the easy posture ($F(1, 6) = 14.71, p < 0.01$) (197 vs. 166 ms). There was also a significant main effect of Posture on the peak deceleration ($F(1, 6) = 18.95$, $p < 0.01$). The maximum deceleration was more important for the complex posture than for the easy one (1152 vs. 801 cm/s^2). This result is in accordance with an increased acceleration/deceleration ratio when the transport phase duration decreases.

The velocity of the right hand at contact with the hold also varies with the posture complexity ($F(1, 6) = 12.07$, $p < 0.05$). When the posture was complex, the velocity at contact was more important than when the posture was easy (18 vs. 13 cm/s), certainly stressing the important role of the hold to provide a passive deceleration for the reaching limb.

Table 2
Ratios of the duration of the acceleration phase over the duration of the deceleration phase

	Hold depth (cm)		
Posture	5	2.5	0.8
Easy	0.9	0.9	0.9
Complex	0.25	0.26	0.25

All results concerning movement up to contact with the hold exhibit a significant influence of postural constraints. This shows that posture influences the organization of grasping movements. Moreover, these results also indicate that, up to the contact with the hold, the depth, and by extension the surface available for the grasp, do not induce changes in the organization and control of the movement.

3.1.2. Behavior after contact with the hold to grasp

Kinetic data were used to examine more precisely the finger–object interaction phase by analyzing the forces applied by the climbers after the contact with the hold. The ANOVA on time to peak force yielded a main effect of Hold ($F(2, 12) = 19.33$, $p < 0.01$). The smaller the hold, the longer the duration of this phase (564, 713, and 917 ms, for the large, medium and small holds, respectively). Moreover, the magnitude of peak force also varied with the size of the hold to grasp ($F(2, 12) = 7.69$, $p < 0.01$). The peak grasping force applied increased with an increase in the depth of the hold (179, 202, and 221 N for the small, medium and large holds, respectively). It is of importance to note that there is no effect of postural constraints on this phase. This highlights the strong differentiation existing between postural constraints which primarily influenced movement up to contact and precision constraints which seem to induce modifications of the grasping movement after the contact with the hold.

3.2. Left-hand movement

3.2.1. Movement until contact with the hold to grasp

The ANOVA yielded a main effect of Hold on the free-motion phase duration of the left hand ($F(2, 12) = 11.21$, $p < 0.01$). The smaller the hold, the shorter the duration of this phase (375, 433 vs. 450 ms, respectively). As only the right hand hold to grasp (anchoring point during the left movement) varied in complexity, the effect of hold on the left movement corresponds to a postural effect. Hence, a smaller right hold induces a more complex posture. This result on the left hand confirms the effect of the postural constraint observed for the right hand movement until contact with the hold.

3.2.2. Behavior after contact with the hold

The ANOVA yielded a main effect of Hold (right hold) on the peak grasping force applied by the left hand ($F(2, 12) = 6.80$, $p < 0.01$). The peak force applied was greater when the right hold was small than when it was medium or large (104, 93 and 91 N). All other effects were not significant ($p > 0.05$).

4. Discussion

The purpose of this study was to examine whether and how a complex posture modifies the kinetic and kinematic organization of grasping movements towards holds of various depths and hence various terminal accuracy constraints. We hypothesized that high postural constraints would lead to a re-organization of the grasping movement by requiring a decrease in the duration of the movement up to contact. Indeed, a prerequisite in rock climbing is the maintenance of an equilibrium. Climbers, in a complex posture, would therefore reduce the duration of the tripodal position whatever the complexity of the hold to grasp. The question is to know how a reduction of this duration is made when other constraints are imposed, and particularly when the hold to grasp becomes smaller.

Our results confirmed that postural constraints, as well as the intrinsic and extrinsic features of the object to be grasped, influence the organization of the grasping movement. More precisely, when climbers were in a complex posture, they increased the duration of the preparatory phase and decreased the duration of the free-motion phase which represented the most unstable phase (tripodal phase, in which only one hand could counteract the backward instability). This movement organization was observed whatever the depth of the hold to grasp, and irrespective of the precision required. The kinematic data showed that this decreased time spent in the tripodal position was also associated with a change in the asymmetry of the movement. That is, the duration of the acceleration phase proportionally increased while the duration of the deceleration phase decreased, again irrespective of the precision required. In other words, subjects speeded-up their movement when the postural constraints increased. This different organization of the movement up to contact has a strong repercussion on the processing of the depth of the hold to grasp (precision requirement). Previous authors have shown that a decreased area available for the grasping movement implies a longer free-motion phase duration (Bootsma et al., 1994; Marteniuk et al., 1987; Gentilucci et al., 1991), by way of a longer deceleration phase. However, the kinetic and kinematic data did not confirm this "precision effect" for movement up to contact with the hold, when grasping movement was performed under high postural constraints. Whatever the depth of the hold (and so the area available for the grasp), this duration remained almost constant. More specifically, velocity, acceleration and deceleration profiles (amplitude and moment of occurrence) did not change with the surface available to perform the grasp, and so with the precision requirements. The "kinematic stability" of the movement until contact with the target suggests that no supplementary visual feedback adjustments were made in relation to the depth of the hold, and that the movement until contact towards different hold depths depended upon the same motor program. This constancy is a major difference with previous studies showing that the free-motion phase was dependent on visually determined information (e.g., Marteniuk et al., 1987, 1990; Meyer, Abrams, Kornblum, Wright & Smith, 1988). As there was no increased feedback control during the free-motion phase according to hold depth, the question of how climbers adjust their movement to the precision requirements of the holds arises, especially when the climbers were in a complex posture (reduction of the duration of the movement up to contact). In previous grasping movements, the hand velocity had to be minimal at the time of contact in order to avoid object displacement. Conversely, in our experiment, the hand velocity at contact was important. Moreover, this velocity increased with an increased postural constraint, suggesting that climbers used the hold as a mechanical stop. Some authors had previously reported the important contribution of the impact with the target for the movement organization (Soechting, 1984; Teasdale & Schmidt, 1991; Zelaznik, Schmidt & Gielen, 1986). Teasdale and Schmidt (1991) showed that the structure of pointing movement was dictated by the amount of impact force subjects were allowed to use to decelerate the limb. More precisely, they showed that the asymmetry in the acceleration-time curve increased (shorter deceleration phase) when large impact magnitudes were allowed at contact.

Once contact with the hold was made, the duration of the adjustments increased when the depth of the hold to grasp decreased. Indeed, the time to attain the peak force after the contact increased with a decreased size of the hold grasped. This increased duration of the finger–object interaction phase was previously shown to be notably sensitive to the weight and to the texture of the target grasped (Weir et al., 1991a, b). Our results showed that, in a complex postural condition, the size of the target could also influence the duration of this phase. This result is reminiscent of Fitts' law (Fitts, 1954). This could be explained by the fact that no new adjustments occurred during the free-motion phase, and by the requirements of the following left-hand movement to perform a right secure grasp. A prolonged duration of the finger–object interaction phase may reflect the time needed to assess and generate this secure grasp. Traditionally, contact with the hold has been viewed as a transition on the information used by the subjects to control their movement (from visual to kinesthetic information). Westling and Johansson (1984) previously showed, through an anesthesia of the glabrous skin mechanoreceptors of the more distal phalanxes, that the proprioceptive information from these receptors was used to apply the functional effective forces when grasping an object. In comparison, our results suggested a more pronounced use of tactile and kinesthetic information to stabilize the grasp when the hold becomes smaller and when the posture is more complex. This different organization of the movement (constant free-motion phase and adjusted finger–object interaction phase) could be dictated by the supplementary postural requirements in rock climbing. The climbers seemed to delay their adjustments after the contact with the hold to reduce the time spent in a tripodal position, particularly when the posture became more complex.

In conclusion, the present findings allow to clearly differentiate control mechanisms prior to and after contact with the hold. Our results indicate that postural constraints and precision requirements are processed separately because each constraint influences the two phases of the grasping movement differently. The strong differentiation between the speed constraints (imposed by the posture), and the precision constraints (imposed by the hold depth in our experiment) suggests the existence of a “hierarchically-organized motor control center, responsible for optimizing performance under a variety of conditions” (Jakobson & Goodale, 1991). In rock climbing, the posture represents the main constraint and implies a different organization of grasping movements to successfully perform the task. This different organization may be achieved through the use of the target as a mechanical stop, and through the extended use of kinesthetic information to control the grasp after contact with the hold. Previous works showed that the extrinsic and intrinsic characteristics of the object to be grasped modify the movement organization. Our results showed that posture also imposes a different organization of the grasping movement, and that rock climbing implies to coordinate precisely grasping activity and postural control.

Future research should be designed to analyze grasping movements in complex postural situations, when targets do not allow to decelerate the movement. This would confirm the important role of the impact. This would also show another organization of the grasping movements when no impact force is allowed at the contact with the hold. The acceleration of the movement, when high postural constraints are imposed, may become problematic for the success of the grasping action.

Another line of direction for further research concerns the precise role of vision in such an activity. Our results suggests that vision may be used in the programming and early phases of the movement and less during the terminal end-phase of the movement. Suppression of the visual information during various phases of the movement or vibration of selected arm muscles could be instructive to understand precisely the respective role of vision and proprioception, and more generally to understand the underlying control processes in various climbing tasks.

Acknowledgements

We thank Gilles Bouchard for technical expertise.

References

Biguer, B., Prablanc, C., & Jeannerod, M. (1984). The contribution of coordinated eye and head movements in hand pointing accuracy. *Experimental Brain Research, 55,* 462–469.

Bootsma, R. J., Marteniuk, R. G., MacKenzie, C. L., & Zaal, F. T. J. M. (1994). The speed-accuracy trade-off in manual prehension: effects of movement amplitude, object size and object width on kinematic characteristics. *Experimental Brain Research, 98*, 535–541.

Bootsma, R. J., & Van Wieringen, P. C. W. (1992). Spatio-temporal organization of natural prehension. *Human Movement Science, 11,* 205–215.

Bouisset, S., & Zattara, M. (1981). A sequence of postural movements precedes voluntary movement. *Neuroscience Letters, 22,* 263–270.

Castiello, U., Bennett, K. M. B., & Stelmach, G. E. (1993). Reach to grasp: The natural response to perturbation of object size. *Experimental Brain Research, 94*, 163–178.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47,* 381–391.

Gahéry, Y., & Massion, J. (1981). Coordination between posture and movement. *Trends in Neurosciences, 81*, 199–202.

Gentilucci, M., Castiello, U., Corradini, M. L., Scarpa, M., Umilta, C., & Rizzolatti, G. (1991). Influence of different types of grasping on the transport component of prehension movements. *Neuropsychology, 29,* 361–378.

Jakobson, L. S., & Goodale, M. A. (1991). Factors affecting higher-order movement planning: A kinematic analysis of human prehension. *Experimental Brain Research, 86,* 199–208.

Johansson, R. S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research, 56,* 550–564.

MacKenzie, C. L., & Iberall, T. (Eds.) (1994). *The grasping hand.* North-Holland, Amsterdam.

MacKenzie, C. L., & Marteniuk, R. G. (1985). Motor skill: Feedback, knowledge, and structural issues. *Canadian Journal of Psychology, 39,* 313-337.

Marteniuk, R. G., Leavitt, J. L., MacKenzie, C. L., & Athenes, S. (1990). Functional relationships between grasp and transport components in a prehension task. *Human Movement Science, 9,* 149–176.

Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology, 41,* 365–378.

Massion, J. (1992). Movement, posture and equilibrium: Interaction and coordination. *Progress in Neurobiology, 38,* 35–56.

Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. K. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review, 95,* 340–370.

Quaine, F., Martin, L., & Blanchi, J.P. (1997). The effect of body position and number of supports on wall reaction forces in rock climbing. *Journal of Applied Biomechanics, 13,* 14–23.

Soechting, J. (1984). Effect of target size on spatial and temporal characteristics of a pointing movement in man. *Experimental Brain Research, 54,* 121–132.

Teasdale, N., & Schmidt, R. A. (1991). Deceleration requirements and the control of pointing movements. *Journal of Motor Behavior, 23,* 131–138.

Weir, P. L., MacKenzie, C. L., Marteniuk, R. G., Cargoe, S. L., & Frazer, M. B. (1991a). The effects of object weight on the kinematics of prehension. *Journal of Motor Behavior, 23,* 192–204.

Weir, P. L., MacKenzie, C. L., Marteniuk, R. G., & Cargoe, S. L. (1991b). Is objects texture a constraint on human prehension?: Kinematic evidence. *Journal of Motor Behavior, 23,* 205–210.

Westling, G., & Johansson, R. S. (1984). Factors influencing the force control during precision grip. *Experimental Brain Research, 53,* 277–284.

Zaal, F. T., & Bootsma, R. J. (1993). Accuracy demands in natural prehension. *Human Movement Science, 12,* 339–345.

Zelaznik, H. N., Schmidt, R. A., & Gielen, C. C. A. M. (1986). Kinematic properties of rapid aimed hand movements. *Journal of Motor Behavior, 18,* 353–372.