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Effect of a leg movement on the organisation of the forces at the holds in a climbing position 3-D kinetic analysis

F. Quaine *, L. Martin, J.P. Blanchi

Laboratoire Sport et Motricite, E.A. 597 UFR.APS, Université Joseph Fourier, BP 53, 38041 Grenoble cédex 9, France

Abstract

This paper describes three-dimensional force data collected during postural shifts performed by individuals simulating rock climbing skills. Starting from a quadrupedal vertical posture, six expert climbers had to release their right footholds and maintain the posture for a few seconds. The analysis of the vertical and the horizontal forces (lateral and antero–posterior forces) applied on the holds was performed before, during and after the onset of the voluntary movement. The results show that the vertical and the horizontal force changes were initiated in synchrony at the same hold. Furthermore, the changes in the forces occurred before the release of the leg. Therefore, they were not a response to, but preparatory for postural change. The force variations were characterized by loadings of the vertical forces and by loadings and unloadings of the horizontal forces. This type of force variation on the holds and their timings seemed necessary to create the dynamic conditions for the onset of the voluntary movement and to counteract the perturbations due to this movement, which balanced the climber on the wall.

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* Corresponding author. Tel.: +33 0476514694, Fax +33 0476514469.

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1. Introduction

In standing bipeds, as in quadrupeds, the displacement of a body segment is often accompanied by muscular activity and mechanical changes involving other segments which contribute to the control of posture and/or balance (Rogers, 1992). This is particularly true for movements involving a limb that has previously been supporting a portion of the body's weight (BW), since alterations in posture are also required to allow for the transfer of the BW to a new support configuration (Rogers and Pai, 1990). Quaine et al. (1996) showed that in rock climbing on a vertical surface, postural control investigations need to analyse the horizontal forces applied on the holds, (i.e. 3-D analysis). These authors studied variations in the positions and in the numbers of holds of the climber and showed that the supporting forces were extensively transferred onto the controlateral holds, with a very slight action of the forces applied on the ipsilateral hold in the tripedal posture. Quaine et al. (1996) used a 4 point–3 point support model with which they compared the differences between two states of static equilibrium. Nevertheless, the question of what occurred during the phase of transition between these stable states arises, i.e. what occurred before and during the limb release?

The purpose of the present study was to design and to describe the postural accompaniments by using the stabilizing and anti-gravitational forces, i.e. the horizontal and the vertical forces, and thus to analyse the forces' organisation on the holds during the transition from 4 to 3 supports in a climbing position.

2. Methods

2.1. Subjects

The population studied here was composed of six climbers of international level. Their average age was 24.1 ± 1.9, the average mass was 73.3 ± 5.1 kg and the average height was 1.75 ± 0.11 m.

2.2. Equipment

The measures were taken from an artificial climbing frame (Quaine et al., 1996). The climbing holds were equipped with three-dimensional strain gauges (Schlumberger, modèle CD 7501, Vélizy villacoublay cedex France). They were fastened to each force transducer which allowed independent measurement of the forces applied on each support.

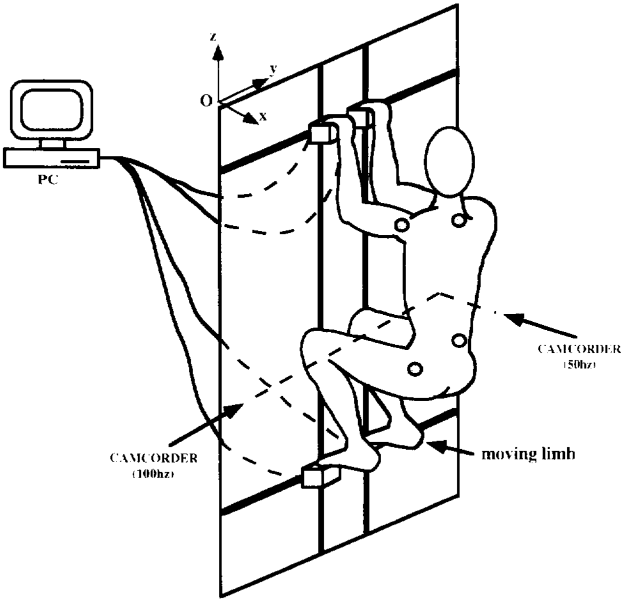

Fig. 1. Schematic representation of the experimental setup. A 3-D load cell is located under each foot and hand support. Two camcorders record the position of reflective markers fixed on the acromion, the great trochanter and on the C7 and the L4–L5 vertrebrae.

Using the three-dimensional strain gauges at each hold, we considered the three components of the force applied on the hold, Rx, Ry, Rz, with respect to the antero–posterior (Ox) the lateral (Oy) and vertical (Oz) axes (Fig. 1). The signals were amplified and recorded on a HP 486 personal computer. The sampling frequency was 100 Hz and the recording time 3 seconds.

The subject's posture was recorded with a camcorder (NAC HSV 400, at a frequency of 100 Hz) set at a distance of 3 meters to the left of the subject. The camcorder recorded reflecting markers positioned onto the shoulder (acromion) and another onto the femur (great trochanter). This camcorder recorded the A/P movements of the trunk. A second camcorder (SONY, 50Hz) was positioned 3 meters behind the subject and recorded the lateral movements of the trunk. For that camcorder, the reflecting markers were positioned at the C7 and L4–L5 vertebrae. The camcorders were synchronized by means of an L.E.D. activated by the experimenter.

The footholds used were characterized by a 1.5 cm wide and 0.7 cm deep ridge, allowing a wedging type of support. The handholds were characterized by a slanting supporting surface favouring hand grips of an adherence type (Salomon and Vigier, 1989). This combination of holds induced a quadrupedal posture in which the forces were mainly applied on the handholds.

2.3. Experimental protocol

The climbing frame was adjusted to the anthropometry of the climbers. The width between the holds was that of the shoulders and the distance between the lower and the upper holds was adjusted so that the subject, standing on the experimental device, had his arms and thighs in a horizontal position (Fig. 1). The investigated position was a constraining position, difficult to maintain, imposed by the experimenter (the upper arms and thighs were horizontal, and visually checked at each try). In order to standardize the experimental condition, an even distribution of the body weight on the holds was requested during the initial position, i.e. 25% of the body weight on each hold. When the position was stable and the body weight correctly distributed, auditory feedback was generated by the PC. The task consisted of letting go of a specified hold at natural speed. The released limb thus had to be kept 2 cm away from the hold in the backward direction. After letting go, the auditory feedback did not continue. The subject went from a 4-support stable posture to a 3-support stable posture that had to be maintained for two seconds before the end of the trial. To avoid an anticipation effect, the subjects were asked to perform five right foot and five right hand movements in a random sequence. Only the data from trials involving foot displacements were analysed.

2.4. Data analysis

The latencies of force changes concerning the three remaining limbs (t_{APA}) were determined on the computer screen. These latencies corresponded to the delays between the onset of the release of the specified limb (t_0) and the times of force changes of the three other limbs. Positive latencies implied that the force changes occurred after t_0, negative latencies implied that they occurred before t_0. The time of lift off of the released limb was represented by t_1. The time at which the tripedal posture was stable was (t_s) obtained when the acceleration of the CG was equal to zero, i.e. when $\sum Rx = 0$, $\sum Ry = 0$ and $\Delta\sum Rz = 0$.

On the recordings, each of the components Rx, Ry and Rz was summed, so that it corresponded to the resultant force $\sum Rx$, $\sum Ry$ and $\sum Rz$ acting at the body center of gravity (CG). $\sum Rz$ was displayed in order to substract the body weight (i.e. $\Delta\sum Rz = \sum Rz - W$, W being the subject's weight). From Newton's law, we computed the accelerations of the center of gravity, respectively $\ddot{X}_{\mathrm{G}}$, $\ddot{Y}_{\mathrm{G}}$, $\ddot{Z}_{\mathrm{G}}$, by using ΣRx, ΣRy and $\Delta \Sigma Rz$ and the subject's mass (m), as follows:

$$\Sigma Rx = m\ddot{X}_{\mathrm{G}},$$
$$\Sigma Ry = m\ddot{Y}_{\mathrm{G}},$$
$$\Delta\Sigma Rz = m\ddot{Z}_{\mathrm{G}}.$$

Numerical integration techniques were used to compute the components of the impulse (Ix, Iy and Iz with respect to (Ox) (Oy) and (Oz) axes) of the net force acting at the CG, as follows:

$$Ix = \int_{t_{\mathrm{APA}}}^{t_s} \Sigma Rx.\mathrm{d}x, \quad Iy = \int_{t_{\mathrm{APA}}}^{t_s} \Sigma Ry.\mathrm{d}y, \quad Iz = \int_{t_{\mathrm{APA}}}^{t_s} \Delta\Sigma Rz.\mathrm{d}z.$$

We proceeded, as previous authors (Philips et al., 1983; Breniere and Do, 1986), with Euler's numerical method, using the formula:

$$Ix(t+h) = Ix(t) + h\Sigma Rx(t),$$
$$Iy(t+h) = Iy(t) + h\Sigma Ry(t),$$
$$Iz(t+h) = Iz(t) + h\Delta\Sigma Rz(t), \quad (h = 0.01\ \mathrm{s}).$$

Variations in the displacement of the CG (Δx, Δy and Δz) were also computed by a subsequent integration, as follows:

$$\Delta x = \frac{1}{m}\int_{t_{\mathrm{APA}}}^{t_s} Ix.\mathrm{d}x, \quad \Delta y = \frac{1}{m}\int_{t_{\mathrm{APA}}}^{t_s} Iy.\mathrm{d}y, \quad \Delta z = \frac{1}{m}\int_{t_{\mathrm{APA}}}^{t_s} Iz.\mathrm{d}z$$

using the same numerical method (Euler's scheme):

$$\Delta x(t+h) = \Delta x(t) + hIx(t),$$
$$\Delta y(t+h) = \Delta y(t) + hIy(t),$$
$$\Delta z(t+h) = \Delta z(t) + hIz(t), \quad (h = 0.01\ \mathrm{s}).$$

2.5. Statistical analysis

The values of the reaction forces were obtained by averaging 5 trials per subject ($n = 6$). The statistical test used to ascertain the significance of the results was the Student paired t-test (two tail). The level of significance chosen was $p < 0.05$.

3. Results and discussion

In static equilibrium, i.e. when $\sum Rx = 0$, $\sum Ry = 0$ and $\Delta \sum Rz = 0$, the horizontal reaction force at RH was directed toward the right and forwards, whereas the reaction force applied at RF was strictly opposed to it, i.e. directed toward the left and backwards. The reaction force at LH was directed toward the left and forwards and the reaction force applied at LF was directed toward the right and backwards. Consequently, the RH force acted directly against the RF force, whereas the LH force counteracted the LF force. Moreover, the lateral force applied at RH acted against the lateral force at LH and the A/P force at

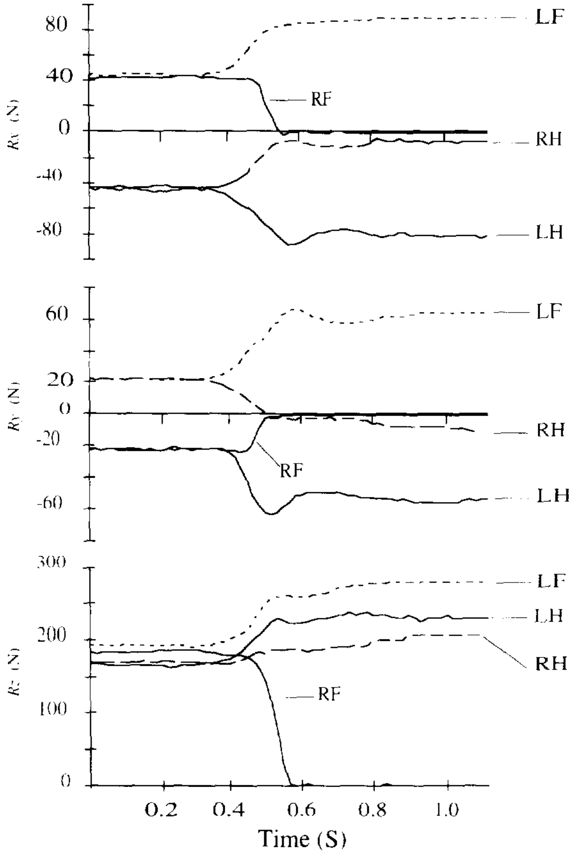

Fig. 2. Typical force variations for Rx, Ry and Rz following a right foot release. RH and LH correspond to the right and left hand, RF and LF correspond to the right and left foot.

RH acted against that at LF (Fig. 2). The upper limbs thus counteracted the backwards falling of the body. These results corroborate the results described in previous experiments (Quaine et al., 1996).

Changes in the forces applied on the holds preceded the onset of the voluntary RF movement. The latencies of the vertical force changes and the latencies of the horizontal force changes at the same hold did not present any statistical difference. Similar results were observed for each hold. This means that the vertical and the horizontal force changes were initiated in synchrony. The force change observed at LH (-140 ± 26 ms) occurred statistically earlier ($p < 0.05$) than the force changes observed at LF (-86 ± 11 ms) and at RH (-66 ± 23 ms). No statistical difference was observed between the force change latencies at LF and RH. Rougier and Blanchi (1992) observed similar results when analysing the posturo-kinetic coordinations of climbers in identical experimental conditions. Nevertheless, the significance of these measurements was limited, since only the vertical forces applied on the holds were taken into account.

The analysis of the changes in the supporting forces revealed two types of variation: the variations in the vertical forces and the variations in the horizontal forces. The organisation of the vertical forces was characterized by their increase on the contralateral holds, mainly on the LF, and by the steadiness of the force applied on RH. The horizontal force changes were characterized by the increase of the supporting force on LF and LH and by the decrease to around zero of the force applied on RH (Fig. 2).

Moreover, the decrease of the horizontal forces on RH and their increase on LH and LF are not conflicting. On the contrary, the 3-D analysis of the forces applied on each hold showed that the lateral RH force acted against the lateral LH force and that the A/P RH force acted against the A/P LF force. The decrease of the lateral and the A/P RH forces induced the same effects at the CG as the increase of the lateral LH and the A/P LF forces. Besides, the RF movement led to effects opposite to those caused by the early unloading of RH (in the quadrupedal position, the forces applied on RF counteracted the forces applied on RH). The results showed that the forces necessary for the balance to be maintained, i.e. the horizontal forces, were displayed on the supports belonging to the side opposite the displaced limb (Quaine et al., 1996). The early loadings and unloadings of the remaining holds may thus be assumed as necessary adjustments which will counteract the perturbations caused by the voluntary limb displacement. Similar conclusions were reached by Bouisset and Zattara (1987). They put forward the hypothesis according to which the early postural adjustments created forces in the body which, when the time came,

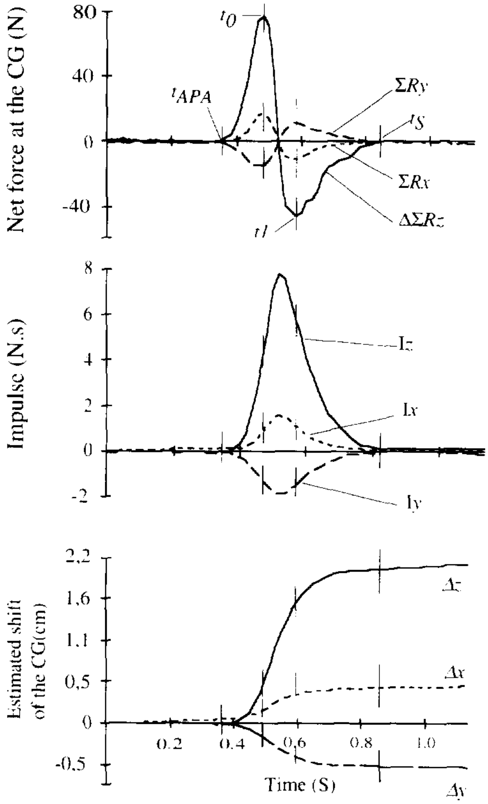

Fig. 3. Ensemble-averaged profiles of the net force. the impulses and the displacement of the CG for five trials of one subject. $\sum Rx$. $\sum Ry$ and $\Delta\sum Rz$ represent the net force along each axis acting at the CG; t_{APA}, t_0, t_1 and t_s are, respectively, the time of first change of force, the onset of focal movement, the time of take-off and the time of tripedal stabilisation. Ix, Iy and Iz represent the A/P, the lateral and the vertical impulses. Δx, Δy and Δz are assumed to be the estimated displacement of the CG along (Ox) (Oy) and (Oz) axes.

balanced the forces due to the focal movement which tended to disturb the postural equilibrium.

This was confirmed by the analysis of the net forces acting at the CG. The timing of the force changes coupled with the direction of the force changes (loading or unloading) induced accelerations of the CG. As can be seen in Fig. 3, $\sum Rx$, $\sum Ry$ and $\Delta\sum Rz$ began before the onset of the voluntary limb movement.

Indeed, at t_0, $\sum Rx$ and $\Delta\sum Rz$ were positive, i.e. corresponded to upward and backward accelerations of the CG; whereas $\sum Ry$ was negative, i.e. corresponded to a lateral acceleration of the CG directed toward the side opposite the mobilized limb. Plotting separately ΣRx, ΣRy and $\Delta\Sigma Rz$ against time clearly showed that the start of the voluntary movement (t_0) always corresponded with the positive maxima of ΣRx and $\Delta\Sigma Rz$ and with the negative maximum of ΣRy, whereas the time of lift off (t_1) was plotted with the negative maxima of ΣRx and $\Delta\Sigma Rz$ and with the positive maximum of ΣRy (Fig. 3). This was observed in all subjects and for each trial. This means that the RF unloading rate was more important than the remaining holds' loading rates.

The gain and the timing of the net force changes were computed into a single dimension, the impulse. As can be seen in Fig. 3, Ix, Iy and Iz were synchronous. The values of Ix, Iy and Iz were respectively 1.18 N.s, -1.21 N.s and 5.61 N.s at to and 1.13 N.s, -1.5 N.s and 5.96 N.s at t_1. The analysis of the impulses showed that a certain amount of momentum was to be created in order to move RF. This amount was not statistically different from the amount at the moment of RF take off. It thus seems that the onset of the RF movement occurred when Ix, Iy and Iz reached a certain value which seemed to correspond to the value of the impulse at the moment when RF took off.

The analysis of the estimated shift of the CG (Fig. 3) indicated that its position remained essentially unmoved, except along the vertical axis. The more important displacement of the CG was upwards, while the displacement in the horizontal plane was very small.

Besides, these estimated shifts of the CG could correspond to the shifts of the center of mass of the moving leg. This could be confirmed by the kinematic analysis of the trunk position. The displacements of the markers fixed on the trunk were nil or negligible. Nevertheless, some positional change may have occurred and its subtleties may have escaped detection, as the system of measurement was limited.

However, before the onset of the voluntary movement (t_0), the CG had already been brought to the new support configuration which corresponded to the tripedal base of support. At t_1, this displacement was almost performed (72% in the vertical direction and 80% in the lateral and A/P directions). This means that when the foot took off from the hold, the postural accompaniment almost ended. The fluctuations after t_1 until t_s corresponded in that case to the end of the RF movement and to the period of tripedal stabilisation.

4. Conclusion

The analysis of force changes during the phase of transition between a stable quadrupedal posture and a stable tripedal posture showed that changes in the forces occurred before the release of the leg. Therefore, the force variations were not a response to a change in posture, but were preparatory for postural change. Moreover, these force changes were characterized by loadings and unloadings of the remaining holds. These force variations and their timings on the supports seemed to serve several purposes: (i) to create, in this type of situation, i.e. a position on a vertical wall, the dynamic conditions needed for the onset of the focal movement, and (ii) to balance with the horizontal forces the postural perturbations due to the focal movement.

References

Bouisset, S. and M. Zattara, 1987. Biomechanical study of the programming of anticipatory postural adjustments associated with a voluntary movement. Journal of Biomechanics 20, 735–742.

Breniere, Y. and M.C. Do, 1986. When and how does steady-state gait movement induced from upright posture begin? Journal of Biomechanics 19, 1035–1040.

Philips, S.J., E.M. Roberts and T.C. Huang, 1983. Quantification of intersegmental reactions during rapid swing motion. Journal of Biomechanics 16, 411–417.

Quaine, F., L. Martin and J.P. Blanchi, 1996. The effect of body position and number of supports on wall reaction forces in rock climbing. Journal of Applied Biomechanics (Accepted).

Rogers, M.W., 1992. Influence of the task dynamics on the organization of interlimb responses accompanying standing human leg flexion movements. Brain Research 579, 353–356.

Rogers, M.W. and Y-C. Pai, 1990. Dynamic transitions in stance support accompanying leg flexion movements in man. Experimental Brain Research 81, 398–402.

Rougier, P. and J.P. Blanchi, 1992. Mesure de la force maximale volontaire à partir d'une posture quadrupodale en escalade: Influence du niveau d'expertise. Science et Sport 7, 19–25.

Salomon, J.C. and C. Vigier, 1989. Pratique de l'escalade. Paris: Vigot.