Influence of steep gradient supporting walls in rock climbing: biomechanical analysis

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Abstract

This study analyses the reaction forces and variations of rock climbing in vertical and overhanging positions. Subjects voluntarily released their right foot and regained equilibrium. In the overhanging position the quadrupedal state was characterised by a significant involvement of the arms to prevent fall. Moreover, the horizontal forces applied to the holds were less important, which suggests that equilibrium was easier to maintain than in the vertical position. The tripedal state was characterised by less extensive contralateral supporting force transfer on the remaining holds in the overhanging position, which reinforces safety.

Keywords: Biomechanics; Equilibrium; Sport rock climbing; Overhanging position

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>Right foot hold (number 1)</td>
</tr>
<tr>
<td>RH</td>
<td>Right hand hold (number 2)</td>
</tr>
<tr>
<td>LH</td>
<td>Left hand hold (number 3)</td>
</tr>
<tr>
<td>LF</td>
<td>Left foot hold (number 4)</td>
</tr>
<tr>
<td>(LF, i, j, k)</td>
<td>Laboratory reference system</td>
</tr>
<tr>
<td>CG</td>
<td>Centre of gravity of the climber</td>
</tr>
<tr>
<td>W</td>
<td>Body weight</td>
</tr>
<tr>
<td>t_q</td>
<td>Time of quadrupedal stabilisation</td>
</tr>
<tr>
<td>t_1</td>
<td>Take off instant of the right foot</td>
</tr>
<tr>
<td>t_s</td>
<td>Time of tripedal stabilisation</td>
</tr>
<tr>
<td>Fh</td>
<td>Horizontal force vector</td>
</tr>
<tr>
<td>Fi</td>
<td>Antero–posterior force vector</td>
</tr>
<tr>
<td>Fj</td>
<td>Lateral force vector</td>
</tr>
<tr>
<td>Fk</td>
<td>Vertical force vector</td>
</tr>
<tr>
<td>X_{CG}(t)</td>
<td>Position of the CG in the x-axis</td>
</tr>
<tr>
<td>Y_{CG}(t)</td>
<td>Position of the CG in the y-axis</td>
</tr>
<tr>
<td>M_{F1/LF}</td>
<td>Moment vector due to the vertical force applied to the right foot (1) with respect to LF (the same abbreviation are used for each moment)</td>
</tr>
</tbody>
</table>

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1. Introduction

Rock climbing is a physical activity in which the upper limbs play the determining role of maintaining equilibrium. Indeed, on a vertical wall, the climber’s centre of gravity is generally located outside the narrow sustentation base which is represented by the holds’ contact surface. This specific situation requires the subjects to apply additional horizontal forces to the hand-holds in order to counteract the body weight moment [1]. Moreover, when a limb is voluntarily released, the supporting forces are specifically distributed on the remaining holds. They increase on the side contralateral to the moving limb, whereas they decrease on the ipsilateral hold [1,2]. Various studies have been made concerning support force variations associated with voluntary movement in a horizontal position, comparing humans and cats equilibrium [3,4]. In those studies, the variations of the forces at work at the supports can generally be explained by the mechanical equilibrium requirement (i.e. \( \Sigma F = 0, \Sigma M = 0 \)). For instance, in Gahe´ry and Nieoullon’s study [3], if the temporal aspects are left aside, the reaction force variations can easily be explained by the computation of the moments about the centre of gravity. In that case, the forces are transferred onto the diagonal opposite the released limb, which leads to a bipedal stance with a resultant moment equal to zero. This has been interpreted as characterising a very stable centre of gravity localised near the loaded limb’s diagonal line [4]. In vertical quadrupedia, a recent study [5] using this type of analysis explains the contralateral transfer of the supporting forces: this process is the only way for the climber to maintain mechanical equilibrium.

Nevertheless, a major difference between the horizontal and vertical position lies in the vertical projection of the line of gravity with respect to the base of support [2]. Hence the results of Quaine et al. [1] which suggest that a continuum of supporting forces changes (from a diagonal to a contralateral transfer) is employed by rock climbers to control balance in quadrupedal positions as the angle of the support surface increases (i.e. from 0 to 90° above the vertical). It thus is likely that the difference in supporting force variations is related to the specific gravitational effect of each position. The diagonal transfer is related to positions inducing a support surface area on to which the centre of gravity is projected (e.g. horizontal position), whereas the contralateral transfer is related to positions with no supporting base (e.g. vertical position). Quadrupedal positions characterised by a sustentation base are not only encountered in horizontal support, but also in overhanging support. In the case of an overhanging position, the vertical projection to the ground of hand holds and foot holds are not mixed up (as in a vertical position). It engenders a significant sustentation base in which the centre of gravity can be potentially projected. Such positions are common in rock climbing, especially during competition events. Until today, no study has been performed in order to investigate the climber’s balance on an overhanging wall. Hence the question of determining whether the supporting forces observed in an overhanging position vary in a similar way to the ones observed in a vertical position following a voluntary hold release. Understanding mechanisms of equilibrium in overhanging positions represents a good way to improve technical knowledge of rock climbing. The aim of this study was thus to characterise the supporting forces arrangements observed in rock climbing and to analyse the results using principles of Newtonian mechanics in static conditions (i.e. \( \Sigma F = 0, \Sigma M = 0 \)). Supporting force changes were observed in both vertical and overhanging positions, before and after a voluntary foot release. They are presented in order to provide as complete an analysis of the balance control in rock climbing as possible.

2. Methods

2.1. Subjects

The population studied was composed of seven climbers at an international level. Their average age was 22 ± 0.4, their average mass was 67.6 ± 3.8 kg, and their average height was 174.8 ± 5.2 cm.

2.2. Equipment

An artificial climbing frame labelled ‘climbing ergometer’ was used for this experiment. The climbing holds were equipped with three-dimensional strain gauges (Schlumberger, model CD 7501, Vélizy-Villacoublay, France). They were fastened to each transducer, allowing us to measure independently the forces applied to each support in the three dimensions of space in a laboratory reference system, using the left foot (LF) as the point of origin. Each transducer yielded data on the vertical (\( F_k \)), lateral (\( F_l \)) and antero–posterior (\( F_t \)) hold reaction forces. The signals from the transducers were amplified (PM instrumentation, ref 1965, Orgeval, France) and recorded on a personal computer. The sampling frequency was 100 Hz, and the recording time was 8 s. Data were filtered with a second-order Butterworth filter (10 Hz low pass cut off frequency). The holds used for this experiment (Freestone©, Argonnay, France) were symmetrical and characterised by a 8 cm width and a 1 cm deep ridge, enabling a wedging type of support for the feet and a ‘crimpy’ type of support for the hands [6]. As it was assumed by this study that no torque was introduced to the holds, many methodological precautions were taken...
in order to disallow the hands/feet to exert any torque on the holds. Those precautions concerned two main aspects: the shape of the holds and the position of the hands/feet on the holds. The holds which were chosen featured a low profile without any edge. These holds required the climber to be suspended by the fingertips (with the first phalanx — ‘crimpy’ prehension) and the palm of the hand was not in contact with the holds, which limited the moments around the lateral and vertical axes. The holds also featured a uniform shape, which enabled the reaction force to be applied to the centre of the hold, the back of which was firmly affixed (with a screw) flush to the extremity of the force transducer. This limited the possible moments around the antero–posterior axis, which was reinforced by the consign given to the climbers to hang onto the centre of the holds and by their position. Moreover, rigid climbing shoes were also used in this experiment, allowing a precise support at the centre of the tiny footholds with the tip of the feet, while suppressing any possible twisting of the shoes. This condition disallowed the feet to exert any torque on the holds.

2.3. Experimental protocol

The climbing frame was adjusted to the body measurements of the climbers. The distance between holds was twice as wide as that of the shoulders, and the distance between lower and upper holds was equal to the height of the subjects. Two positions have been tested. The first one was the reference vertical position, with the climbing ergometer set vertically in the laboratory reference system. The second position, with the same holds arrangement, was overhanging: the ergometer had been adjusted so that the holds plane was inclined 10° to the vertical (Fig. 1). The climbers were asked to adopt the least constraining position with the forearms vertically placed. They all adopted the same position for both experimental conditions, with the trunk close to the plane of the holds. The task consisted in maintaining a stable quadrupedal posture for 3 s and release of a specified hold, without a jerk. The amplitude of the movement had to be small, for the centre of gravity (CG) to remain basically unmoved. The released limb thus had to be kept 2 cm away from the hold, upwards. The subjects went from a 4-support stable posture to a three-support stable posture, which they had to maintain for 5 s before the end of the trial. In order to avoid a learning effect, the subjects were asked to perform five right foot and five left foot movements in a random sequence. Only data from trials involving the right foot displacements were analysed.

2.4. Analysis of data

The forces acting at the holds were analysed during stable quadrupedal and tripedal state. Two instants were chosen with respect to \( t_1 \) (take off instant): \( t_q = t_1 - 1500 \) ms for the quadrupedal state, and \( t_s = t_1 + 2000 \) ms for the tripedal state. Holds are numbered from 1 to 4 (1 = right foot, 2 = right hand, 3 = left hand, 4 = left foothold). These numbers are used in the general equations governing the movement of the climber. The horizontal forces \( (F_h) \) were computed on each hold as follows:

\[
F_h = \sqrt{\|F_i\|^2 + \|F_j\|^2}
\]

For each position, the following equations explain how to compute the moments around each axis in reference to the left foot:

*Vertical position:*

\[
\sum_{i=1}^{4} M_{Fi/LF} + \sum_{j=1}^{4} M_{Fj/LF} + \sum_{k=1}^{4} M_{Wk/LF} = Mi
\]

\[
\sum_{i=1}^{4} M_{Fi/LF} + \sum_{j=1}^{4} M_{Wj/LF} = Mj
\]

\[
\sum_{i=1}^{4} M_{Fi/LF} = Mk
\]
The computation of the body weight's moment variation requires the estimation of the coordinates of the CG ($X_{CG}(t); Y_{CG}(t)$). The expansion of the equations Eqs. (1)–(4) along the lateral and antero–posterior axis leads to the following scalar equations needed to solve the initial coordinates of the CG:

**Vertical**

\[ Y_{CG}(t_q) = \frac{\sum_{i=1}^{4} M_{f_k,i,F} + \sum_{j=1}^{4} M_{f_j,i,F}}{W} \]

\[ X_{CG}(t_q) = \frac{\sum_{i=1}^{4} M_{f_i,i,F}}{W} \]

**Overhanging**

\[ Y_{CG}(t_q) = \frac{\sum_{i=1}^{4} M_{f_k,i,F} + \sum_{j=1}^{4} M_{f_j,i,F}}{W} \]

\[ X_{CG}(t_q) = \frac{\sum_{i=1}^{4} M_{f_i,i,F} + \sum_{j=1}^{4} M_{f_j,i,F}}{W} \]

with $X_{CG}(t_q)$ and $Y_{CG}(t_q)$ the antero–posterior and lateral coordinates of the CG during the quadrupedal stable state ($t_q$) and $W$ the body weight.

Displacement of the CG along each axis were then computed as follows:

\[ X_{CG}(t) = X_{CG}(t_q) + \frac{1}{m} \int_{t_q}^{t} \left( \sum_{i=1}^{4} F_i(t) \right) dt \]

\[ Y_{CG}(t) = Y_{CG}(t_q) + \frac{1}{m} \int_{t_q}^{t} \left( \sum_{j=1}^{4} F_j(t) \right) dt \]

Newton–Cote’s numerical method (order 2) was used for integrations.

The resulting moment around each axis about the left foot can thus be written as follows:

**Vertical position**

\[
\begin{align*}
M_{f_k,1,F} + M_{f_k,2,F} - M_{f_j,1,F} + M_{f_j,2,F} - M_{w_k,L,F} = M_i \\
M_{w_k,1,F} - M_{f_j,2,F} - M_{f_j,1,F} - M_{f_k,1,F} = M_j \\
M_{f_j,2,F} - M_{f_j,1,F} = M_k
\end{align*}
\]

Clock-wise moments were negative and counterclock-wise moments were positive.

### 2.5. Statistical analysis

The values of the reaction forces and moments were obtained by averaging five trials per subject ($n = 7$). Analysis of variance (ANOVA) with repeated measures were used to establish the significance of the results. The independent variables were the position (vertical or overhanging) and the number of supports (quadrupedal or tripodal state). The dependant variables were the magnitude of the forces applied to each support and their moments around each axis. The level of significance chosen was $P < 0.05$.

### 3. Results

The results are presented in two sections: the first one concerns the analysis of the reaction forces, the second concerns the analysis of the moments.

Typical forces applied to the holds are presented in Fig. 2. Concerning the lateral component, whatever the position, left foot and right hand supports were opposed to right foot and left hand supports. The antero–posterior forces applied to the hands were opposed to those applied to the feet. When the subject released his right foot, force variations were observed on the three remaining supports along each axis. Whatever the position, these variations were characterised by an increase of the vertical (Fig. 2a), lateral (Fig. 2b) and antero–posterior (Fig. 2c) forces applied to the contralateral holds (i.e. left hand and left foot) associated with a decrease of the forces applied to the ipsilateral hold (i.e. right hand). The statistical analysis of these variations is represented in Tables 1 and 2. Table 1 indicates the vertical force values observed at the supports in both positions during the quadrupedal and tripodal steady states (i.e. $t_q$ and $t_l$). The results show that in the quadrupedal stance, the subjects exerted higher force intensities on the foot supports ($395 \pm 54$ N) in the vertical position, while the hand supports were preferred in the overhanging position ($432 \pm 54$ N). In our attempt to present clear results, the lateral and antero–posterior forces were analysed into a single horizontal force applied to each hold (see Section 2). Table 2 shows the magnitudes of these forces in both positions during the four and three-supports posture. Results indicate significantly lower horizontal forces applied to
Fig. 2. One typical trial showing forces variations along the vertical (a), lateral (b) and antero–posterior (c) axes following a right foot release, in vertical and overhanging positions. RH and LH correspond to the right and left hand, RF and LF to the right and left foot. The quadrupedal and tripedal steady states are represented by $t_q$ and $t_s$, $t_1$ represents the time of lift off.

Table 1
Mean vertical forces and standard deviation (N) applied to the holds at $t_q$ (quadrupedal state) and $t_s$ (tripedal state) in vertical and overhanging positions$^a$

<table>
<thead>
<tr>
<th>Quadrupedal state ($t_q$)</th>
<th>Tripedal state ($t_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH</td>
<td>LH</td>
</tr>
<tr>
<td>Vertical position</td>
<td></td>
</tr>
<tr>
<td>144 ± 39</td>
<td>151 ± 47</td>
</tr>
<tr>
<td>Overhanging position</td>
<td>218 ± 27$^b$</td>
</tr>
</tbody>
</table>

$^a$ RH, right hand; LH, left hand; RF, right foot; LF, left foot.
$^b$ Significant difference between both positions.
$^c$ Significant difference between $t_q$ and $t_s$ ($P<0.05$).

each support in the overhanging position before the foot release. In the three-supports posture, results show that the horizontal forces applied to the contralateral holds increased significantly less in the overhanging position. Moreover, the decrease observed at the ipsilateral hold was significantly less important in the overhanging position. In fact, in the vertical position, the horizontal force at the right hand virtually decreased
down to zero, whereas it decreased to $48 \pm 10$ N in the overhanging position. The horizontal net forces (i.e., $\Sigma F_h$) were substantially more important in the vertical position ($288 \pm 42$ N) than in the overhanging one ($222 \pm 12$ N), whatever the number of supports (quadrupedal or tripod state).

The analysis of the centre of gravity displacements showed that it was not displaced from four to three supports (no significant difference of the location of the CG were observed across the quadrupedal and tripodal stance in both positions). Therefore, the body weight moment around the lateral and antero–posterior axis remained constant from four to three supports as shown in Fig. 3b and c. The reaction moments observed for a typical trial are indicated in Fig. 3. The evolution of the moments around the antero–posterior axis (Fig. 3c) indicates no supplementary moment in the overhanging position. In both positions, the variations observed after the hold release indicate a decrease of the moments induced by the forces applied to the right hand ($M_{Fj2/LF}$ and $M_{Fj2/RF}$) and an increase of the moment induced by the lateral force applied to the left hand ($M_{Fj1/LF}$). Although the polarity of the moments was identical in both positions, magnitude differences were obvious. The statistical analysis (Table 3) shows that the decrease of the moments created by the forces at the right hand appeared to be significantly less important in the overhanging position. The moment induced by the lateral component did not drop to zero as in the vertical position and the moment due to the vertical component slightly decreased in the overhanging position ($-26 \pm 9\%$ vs $-40 \pm 13\%$). The increase of the moment at the left hand appears to be substantially more important in the vertical position. Around the lateral axis (Fig. 3b), in the overhanging position, four reaction moments counteracting the body weight moment were observed, whereas only two components were noted in the vertical position. The moment of the body weight appeared to be significantly more important in the overhanging position than in the vertical one ($274 \pm 41$ N m vs $170 \pm 34$ N m). All but the moment of the body weight were influenced by the number of supports in any position. More precisely, in the three-supports posture, the moment created by the antero–posterior force applied to the left hand ($M_{Fj1/LF}$) was substantially more important in the vertical position than in the overhanging one ($-178 \pm 44$ N m vs. $-74 \pm 29$ N m). The moment created by the right hand ($M_{Fj2/LF}$) amounted to $-42 \pm 16$ N m in the overhanging position, while it was nearly equal to zero ($-5 \pm 4$ N m) in the vertical position. In the vertical position, the vertical forces did not create any moment, whereas in the overhanging position, the moments induced by the vertical forces applied to the right hand ($M_{Fj2/LF}$) amounted to $-70 \pm 4$ N m and significantly decreased to $-52 \pm 5$ N m in tripodia. The moment of the vertical force applied to the left hand ($M_{Fj2/RF}$) was equal to $-68 \pm 5$ N m in quadrupedia and significantly increased to $-77 \pm 7$ N m in tripodia. Moments around the vertical axis are presented in Fig. 3a. In the vertical position, the moment of the antero–posterior force applied to the right foot ($M_{Fj1/LF}$) was counterbalanced by the moment created by the antero–posterior force at the right hand ($M_{Fj2/LF}$) ($-45 \pm 14$ N m and $45 \pm 15$ N m, respectively). When the right foot was released, the moment of the antero–posterior force at the right hand significantly decreased to zero. Several differences were observed in the overhanging position since two supplementary moment components created by the lateral forces were noted. The moment of the antero–posterior force at the right hand ($M_{Fj2/LF}$) was counterbalanced by the moment induced by the antero–posterior force applied to the right foot ($M_{Fj1/LF}$) and the moment of the lateral force at the right hand ($M_{Fj2/RF}$) was counterbalanced by the moment of the lateral force at the left hand ($M_{Fj3/LF}$). After the hold release, the moment of the antero–posterior force at the right foot decreased down to zero. Both antero–posterior and lateral moments at the right hand signifi-

### Table 2

Mean horizontal forces (N) and standard deviation applied to the holds at $t_q$ (quadrupedal state) and $t_t$ (tripedal state) in vertical and overhanging positions

<table>
<thead>
<tr>
<th>Quadrupedal state</th>
<th>Tripedal state</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH</td>
<td>LH</td>
</tr>
<tr>
<td><strong>Vertical position</strong></td>
<td></td>
</tr>
<tr>
<td>$85 \pm 21$</td>
<td>$78 \pm 14$</td>
</tr>
<tr>
<td><strong>Overhanging position</strong></td>
<td></td>
</tr>
<tr>
<td>$62 \pm 10^b$</td>
<td>$67 \pm 12^b$</td>
</tr>
</tbody>
</table>

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*RH, right hand; LH, left hand; RF, right foot; LF, left foot.

*Significant difference between both positions.

*Significant difference between $t_q$ and $t_t$ ($P<0.05$).
Fig. 3. One typical trial showing moments evolution around the vertical (a), lateral (b) and antero–posterior axis (c), following a right foot release, in vertical and overhanging positions. See nomenclature for abbreviations. Positive moments tend to rotate the climber counterclock-wise, while negative moments tend to rotate the climber clockwise.

Table 3
Mean moments and standard deviation (N m) around the antero–posterior axis in reference to the left foot

<table>
<thead>
<tr>
<th></th>
<th>Quadrupedal state (t_q)</th>
<th>Tripedal state (t_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vertical position</td>
<td>Overhanging position</td>
</tr>
<tr>
<td>( M_{F2/LF} )</td>
<td>83 ± 10^b</td>
<td>117 ± 17</td>
</tr>
<tr>
<td>( M_{F1/LF} )</td>
<td>−93 ± 21^b</td>
<td>−114 ± 7</td>
</tr>
<tr>
<td>( M_{F3/LF} )</td>
<td>134 ± 14^b</td>
<td>175 ± 8</td>
</tr>
<tr>
<td>( M_{W1/LF} )</td>
<td>148 ± 23^b</td>
<td>90 ± 21</td>
</tr>
<tr>
<td>( M_{R/LF} )</td>
<td>−252 ± 28</td>
<td>−267 ± 22</td>
</tr>
</tbody>
</table>

^a Indicates an effect due to the number of supports (quadrupedal or tripedal state).

^b Indicates an effect of the position (vertical or overhanging) \((P<0.05)\).

Significantly decreased (from \(20 ± 2\) N m to \(13 ± 3\) N m) and were balanced by the significant increase of the lateral moment at the left hand (from \(−21 ± 3\) N m to \(−27 ± 4\) N m).
4. Discussion

The main result of this study is the characterisation of the supporting force changes observed in vertical and overhanging climbing positions. The analysis of the magnitude of these forces indicates higher vertical force values applied to the feet in the vertical position (57 ± 12% of the body weight), whereas the vertical forces applied to the handholds were more important in the overhanging position (62 ± 9% of the body weight). This means that the arms, which preponderantly stabilise the body in a vertical position [1], counteract the vertical collapse in an overhanging position. When the climber voluntarily released his right foot, different force variations were observed according to the position. Considering the vertical position, tripedal steady state was characterised by a contralateral distribution of the reaction forces on the holds and by the decrease of the forces applied to the ipsilateral hold. Different results were observed in the overhanging position, since the forces slightly decreased on the ipsilateral hold. In that case, body balance is performed using the three remaining holds and reflect a stable position. Previous studies exclude that this result is induced by the different initial force distribution on the holds [2,8]. Hence the less extensive contralateral force transfer in the overhanging position, which means that the distribution of the forces was more homogeneous on the three remaining supports. Moreover, the horizontal supporting forces value is less important in the overhanging position. According to Quaine et al. [1], these results indicate that the overhanging position is easier to maintain from a mechanical point of view. This seems to be paradoxical regarding the physiological studies performed by Watts and Drobish [7]. They showed an increase of the energy cost per distance climbed and a significant blood lactate accumulation for overhanging positions. In fact, from a functional point of view, the legs are more adapted to support the body weight than the arms, which can explain the higher physiological activity of the subjects in overhanging positions.

The double integration of the net forces showed that the performers adjusted the supporting forces with insignificant positional change when the limb was released, either in the vertical or in the overhanging position. Consequently, the body weight moments remained constant. In the vertical position the drastic decrease of the antero–posterior ipsilateral force is necessary to restore rotational equilibrium around the vertical axis, which induces the increase of the antero–posterior force on the left hand. This counteracts the body weight moment around the lateral axis and restores translational equilibrium along the antero–posterior axis. The increase of the lateral force on the left hand is necessary to counteract the moment of the body weight around the antero–posterior axis, with the additional help of the decrease of the moment produced by the lateral force on the right hand [5]. This last conclusion is also valid in the overhanging position, since the latter does not induce supplementary moment component. Indeed, the only differences are the more important and the weaker moment values at the right hand and right foot, respectively. This is related to the higher vertical forces applied to the hand supports in the overhanging position. In the tripedal state, the moment of the forces applied to the right hand slightly decreases which is consistent with the less extensive transfer of the supporting forces previously observed.

The conclusions in the vertical position around the vertical and lateral axes are not valid in the overhanging position, since additional lever arms are at work, which leads to supplementary moment components. The body weight moment around the lateral axis in the overhanging position is thus virtually twice as important as the one in the vertical position. This moment is counteracted by moments induced by the antero–posterior forces (i.e. idem vertical position) and by additional moments induced by the vertical forces applied to the hand holds. Therefore, the increase of the vertical force applied to the hands necessarily increases both work against vertical collapsing and stabilising actions. This represents a major difference with the vertical position, since vertical forces only avoid vertical collapse and do not counterbalance the body weight moment. After the foot release, the decrease of the moments induced by the forces exerted on the right hand is counterbalanced by an increase of the left hand moments with the same intensity in order to equilibrate the constant moment of the body weight. The analysis of the moments around the vertical axis shows that two components (induced by the antero–posterior forces) were at work in the vertical position, whereas four components (induced by the lateral and antero–posterior supporting forces) were observed in the overhanging position. When the right foot is released, the three remaining moments are thus combined in order to counterbalance the loss of the support. This result differs from those observed in the vertical position where a unique solution was shown [5]. The supplementary moments encountered in the overhanging position led to supplementary solutions to keep balance. The scheme operated by the climbers to restore equilibrium after the foot release seems to be a compromise of all the possible solutions.

Our study thus suggests that equilibrium preservation is easier to manage in the overhanging position since (i) the external constraints are weaker (existence of a substantial base of support); and (ii) the vertical force applied to the holds balances both the body weight and his resulting moment (supplementary lever arms). This is fundamentally different from equilibrium preservation observed in vertical quadrupedia since the vertical force applied to the holds only avoid vertical collapse.
whereas the body weight moment is only counterbalanced by horizontal forces applied to the holds.

5. Conclusion

The mutual analysis of forces and moments is necessary to understand the relation between the wall inclination and the forces transfer in rock climbers. The horizontal forces are less important in the overhanging position because of the existence of a base of support, which suggests that the postural constraint is weaker and the position easier to maintain from a mechanical point of view. Nevertheless, the forces are not exerted onto the same supports since the upper limbs mainly support the body weight, which can explain the higher energy expenditure in the overhanging position [7]. To better address the functional consequences of the arms involvement, an analysis of the moments of force patterns at various joints (e.g. elbow and shoulders) could be conducted. Moreover, when a hold is voluntarily released, forces are transferred onto the contralateral holds, but this transfer appeared to be less extensive in the overhanging position. This more homogenous force distribution may be interpreted as an equilibrium strategy for reinforcing safety. In case of an unexpected release of one of the three remaining supports, equilibrium preservation would be easier to maintain. Conversely, with a force transfer predominantly contralateral, the sudden loss of one of these supports would typically induce a fall.

References