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A biomechanical study of equilibrium in sport rock climbing

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Abstract

One of the main objectives of the experiment reported in this article was to analyze the arrangement of the forces applied to the holds accompanying a voluntary right foot release in the hanging rock climber. The three dimensional reaction forces applied to the holds were measured using four holds equipped with strain gauges. The force arrangement after the release consisted of a tripedal stance on the three remaining holds for the vertical forces, and of a bipedal stance on two laterally opposite holds (left foot and left holds) for the horizontal forces. The general significance of the results was analyzed with respect to the mechanism of static equilibrium. However, before conclusions can be drawn, other climbing movements and positions must be analyzed.

Keywords: Sport rock climbing; Biomechanics; Mechanical equilibrium; Balance control

1. Introduction

Rock climbing is a unique sporting activity, in that the role of the upper limbs and the predominantly vertical motion distinguish it from all other land-based movements. Most of the studies on sport rock climbing have investigated physiological requirements of the activity [1–4], anthropometric factors [5,6] or upper limb injuries [7,8]. From a biomechanical point of view, the study of the supporting forces at the holds provides an excellent assessment of the activity. It explains the climber's adjustments to external perturbations (e.g. a hold release) and so leads to an understanding of the mechanical events associated with falls [9]. This can be extended beyond rock climbing, for example, climbing a ladder is identical to rock climbing and presents similar biomechanical constraints [10,11].

A rock climber at rest on a vertical wall keeps his balance due to horizontal supporting forces. In the case of a voluntary hold release, the vertical and horizontal forces are not equally distributed on the remaining holds. They increase on the controlateral holds, whereas the vertical force remains constant and the horizontal forces decrease to zero on the ipsilateral hold [9]. Although the initial positions were different, similar results were observed with children [12]. These force variations seem to produce the conditions necessary for the onset of the voluntary release and counteract the induced perturbations, which balance the climber on the remaining holds. These results were in general accordance with the mechanisms of postural adjustments [13], but they present an insufficient mechanical analysis. In fact, the authors [9,12] only performed the analysis of the reaction supporting forces and disregarded the analysis of the moment reactions.

This study was undertaken to improve the knowledge of rock climbing biomechanics. Principles of Newtonian mechanics were used in order to understand how the vertical and the horizontal forces were distributed on the holds and how they changed after a hold had been voluntarily released.

2. Methods

2.1. Subjects

The population studied consisted of six climbers of

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international level. Their average age was 24 ± 1.9, their average mass was 73 ± 5.1 kg and their average height was 1.75 ± 0.11 m.

2.2. Kinetic measuring procedures

The measurements were taken from an artificial climbing frame as presented in Fig. 1. The climbing holds were attached to strain-gauged transducers that measured forces in three orthogonal directions in the laboratory reference system {LF; $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$} having as origin the point of application of the left foot supporting force (LF). The location of LF corresponded to the central area of the left foot hold. The transducers did not measure torques. The holds were numbered from 1 to 4 (1 = RF hold, 2 = RH hold, 3 = LH hold and 4 = LF hold). These numbers were used when writing general equations governing the movement of the climber. The signals were amplified and recorded on a HP 486 personal computer. The sampling frequency was 100 Hz and the recording time 3 s. The foot holds used were characterized by a slanting supporting surface favoring hand grips of an adherence type [14]. This combination of holds induced positions in which the forces were mainly applied to the hand holds.

The climbing frame was adjusted to the anthropometry of the climbers. The width between the holds corresponded to that of the shoulders and the distance between the lower and the upper holds was adjusted while a subject stood on the experimental device with his upper arms and thighs horizontal. The position was visually checked at each trial by the experimenter. In order to standardize the initial supporting force arrangement, an even distribution of the body weight was required (i.e. 25% ± 5%). When the position was correct and the body weight correctly distributed, an auditory signal was generated by the PC. At that moment, the experimenter informed the subject which hold must be released. The task consisted in releasing the specified hold without any velocity requirement. The released limb thus had to be kept ≈ 2 cm away from the hold in the upward direction. After letting go, the auditory signal ceased. The subject went from a 4-support to a 3-support stable position. The subjects were asked to perform five right foot and five left hand movements in a random sequence, so that they could not anticipate the limb to release. Only the data from trials involving foot displacements were analyzed.

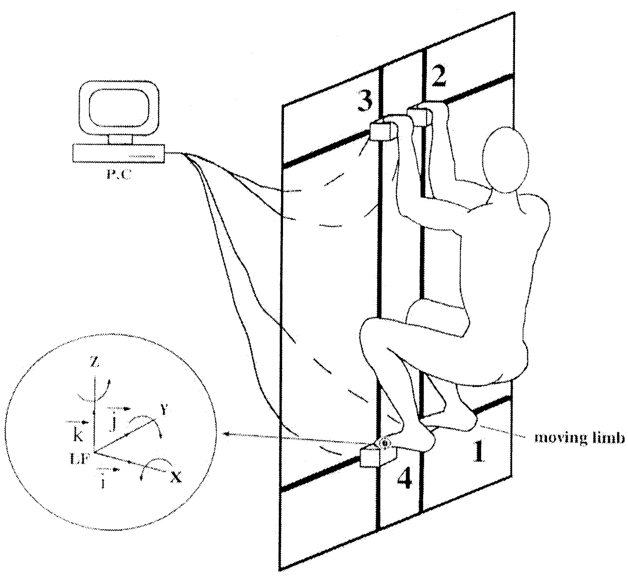

Fig. 1. Experimental device. Each support is equipped with strain gauges (3-D). The three components of the force applied to each hold are recorded with respect to the reference system (LF, $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$). Clock-wise moments were negative and counterclock-wise moments were positive. The holds were numbered from 1 to 4 (1 corresponded to the right foot hold and 4 corresponded to the left foot hold).

2.3. Reaction forces and moments computation

The spatial motion of the climber was defined by two general equations governing the translation and the rotation in the reference system:

$$\sum F = \text{m}\boldsymbol{a} \tag{1}$$

$$\sum M = I\boldsymbol{\alpha} \tag{2}$$

The sum of all the supporting forces (ΣF) acting on the center of mass equals the product of the mass (m) of the climber by its linear acceleration (a). The sum of the moment reactions (ΣM) about the left foot hold equals the product of the moment of inertia (I) of the climber by its angular acceleration ($\boldsymbol{\alpha}$).

It was assumed that the hands and the feet did not exert a torque on the holds. This was reinforced by the fact that some methodological precautions were taken concerning the type of holds (thin thickness and appropriate form so that the reaction force was applied to the central area of the hold which exactly met the extremity of the force transducer), the arrangement of the holds (width of the shoulders), and the position of the climber on the holds (arms and thighs were horizontal in the sagittal plane).The projection of equations (1) and (2) along each axis gives:

$$(1) \Leftrightarrow \begin{cases} \sum_1^4 F\boldsymbol{i} = \text{m}a\boldsymbol{i} \\ \sum_1^4 F\boldsymbol{j} = \text{m}a\boldsymbol{j} \quad \text{and} \\ \Delta\sum_1^4 F\boldsymbol{k} = \text{m}a\boldsymbol{k} \end{cases}$$

$$(2)\Leftrightarrow\begin{cases}\sum_1^4 M_{Fk/\mathrm{LF}}+\sum_1^4 M_{Fj/\mathrm{LF}}+MW_{k/\mathrm{LF}}=M\boldsymbol{i}\\ \sum_1^4 M_{Fk/\mathrm{LF}}+\sum_1^4 M_{Fi/\mathrm{LF}}+MW_{k/\mathrm{LF}}=M\boldsymbol{j}\\ \sum_1^4 M_{Fi/\mathrm{LF}}=\mathrm{M}k\end{cases}$$

Σ_1^4represented the sum of the forces applied to four holds.

The net vertical force was displayed in order to subtract the body weight (i.e.$\Delta\Sigma_1^4 F\boldsymbol{k}=\Sigma_1^4 F\boldsymbol{k}-W\boldsymbol{k}$, $W\boldsymbol{k}$ being the subject's weight).The expansion of equation (2) along the lateral and antero/posterior axes leads to the following scalar equations to solve the initial coordinates of the center of gravity:

$$\begin{cases}Y\mathrm{CG}(t\mathrm{Q})=\dfrac{\sum_1^4 M_{Fk/\mathrm{LF}}+\sum_1^4 M_{Fj/\mathrm{LF}}}{\mathrm{W}}\\ X\mathrm{CG}(t\mathrm{Q})=\dfrac{\sum_1^4 M_{Fi/\mathrm{LF}}}{W}\end{cases}$$

with $X_{\mathrm{CG}}(t_{\mathrm{Q}})$ and $Y_{\mathrm{CG}}(t_{\mathrm{Q}})$ the antero/posterior and lateral coordinates of the CG during the quadrupedal stable state.

In order to determine changes in the moments, it was necessary to estimate the displacements of the CG, $X_{\mathrm{CG}}(t)$ and $Y_{\mathrm{CG}}(t)$. The net force was integrated once to derive velocity, and a second time to derive position [15,16]. During the quadrupedal stable state, the velocity of the climber was equal to zero and the initial position of the CG was equal to $X_{\mathrm{CG}}(t_{\mathrm{Q}})$ and $Y_{\mathrm{CG}}(t_{\mathrm{Q}})$ which represented the constant of integration. The coordinates of the CG were thus computed as follows:

$$\begin{cases}X\mathrm{CG}(t)=X\mathrm{CG}(t\mathrm{Q})+\dfrac{1}{\mathrm{m}}\displaystyle\int_{t\mathrm{APA}}^{t\mathrm{S}}\left(\int\sum_1^4 F\boldsymbol{i}(t)\mathrm{d}t\right)\mathrm{d}t\\ Y\mathrm{CG}(t)=Y\mathrm{CG}(t\mathrm{Q})+\dfrac{1}{\mathrm{m}}\displaystyle\int_{t\mathrm{APA}}^{t\mathrm{S}}\left(\int\sum_1^4 F\boldsymbol{j}(t)\mathrm{d}t\right)\mathrm{d}t\end{cases}$$

Newton's numerical method (order 2) was used for integration:

$$\int_a^b f(x)\mathrm{d}x\approx\frac{n}{2}\left[f(a)+f(b)+2\sum_{i=1}^{n-1}f(xi)\right]$$

The equations governing the rotation movement about the left foot can thus be written as follows:

$$(3)\Leftrightarrow\begin{cases}M_{Fk1/\mathrm{LF}}+M_{Fk2/\mathrm{LF}}-M_{Fj2/\mathrm{LF}}+M_{Fj3/\mathrm{LF}}-M_{Wk/\mathrm{LF}}=M\boldsymbol{i}\\ M_{Wk/\mathrm{LF}}-M_{Fi2/\mathrm{LF}}-M_{Fi3/\mathrm{LF}}=M\boldsymbol{j}\\ M_{vi1/\mathrm{LF}}-M_{Fi2/\mathrm{LF}}=M\boldsymbol{k}\end{cases}$$

Clock-wise moments were negative and counterclock-wise moments were positive (Fig. 1).

2.4. Analysis of data

The values of the reaction forces were obtained by averaging five trials per subject (n $\pm$ 6). The distribution of the results was assessed by Wilcoxons's non parametric statistical U-tests. Vertical and net force latencies were compared between the remaining holds (i.e. RH, LH and LF). The values of the forces and moments computed for each direction and each support in the quadrupedal static equilibrium were compared to the values computed in the tripedal static equilibrium. The result was considered significant if the threshold of probability was at least equal to 0.05.

3. Results

During the initial quadrupedal position, the horizontal reaction force (Fig. 2) applied to the right hand hold (RH) was positive along the lateral axis and negative along the antero-posterior axis. The horizontal reaction force applied to the right foot hold (RF) was opposed to it, i.e. negative along the lateral axis and positive along the antero-posterior axis. Consequently, the RH force acted against the RF force. Similarly, the force applied to the left hand hold (LH) counteracted the force applied to the left foot hold (LF). The sum of the vertical forces applied to the holds equaled the weight of the climber.

The moment around the vertical axis due to the horizontal force applied to RF was negative, which tended to rotate the climber clock-wise, whereas the moment of the force applied to RH was opposed to it and rotated the climber counterclock-wise (Fig. 3a). Rotational equilibrium around the lateral axis (Fig. 3b) was achieved through the net clockwise moment of the antero-posterior forces applied to LH and RH, which balanced the counterclock-wise moment of the body weight. The moment around the antero/posterior axis (Fig. 3c) due to the lateral force applied to RH associated with the moment of the body weight tended to rotate the climber clock-wise. They were balanced by the moment of the lateral force applied to LH, and moments of the vertical force applied to RF and RH, which rotated the climber counterclock-wise. More precisely, the moment of the lateral force applied to RH

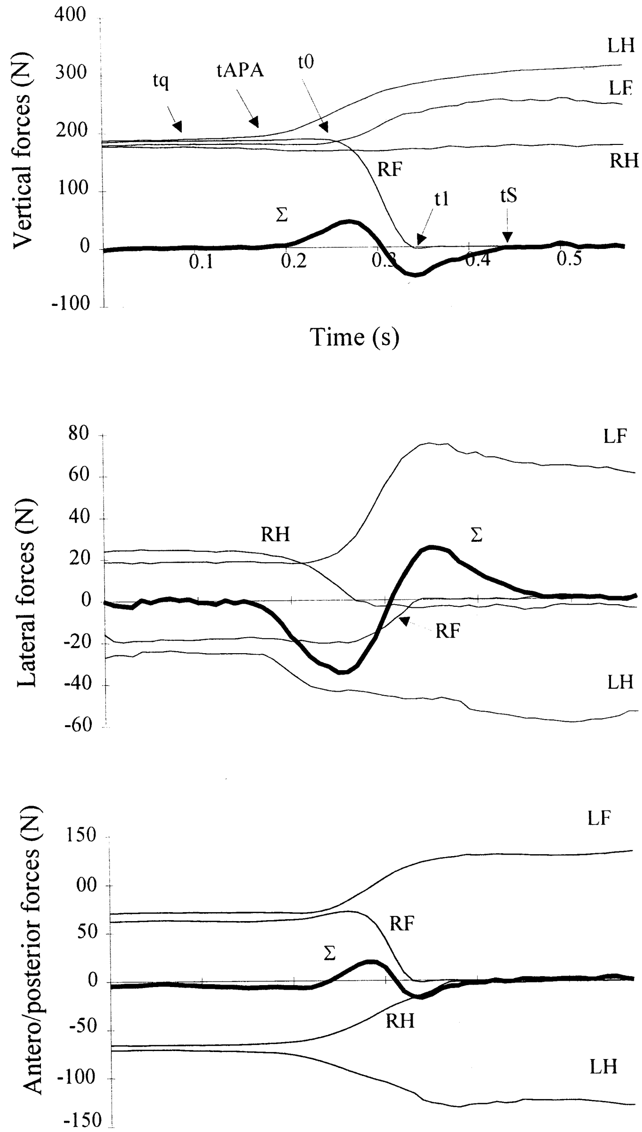

Fig. 2. Forces variations for one trial. RH and LH correspond to the right and left hand, RF and LF correspond to the right and left foot. Σ correspond to the net forces along each axis. t_Q, t_{APA}, t_0, t_1 and t_S are respectively the time of quadrupedal stabilization, of first force change, the onset of right foot release, the time of take-off and the time of tripedal stabilization.

counterbalanced the moment of the lateral force applied to LH, and the net moment of vertical forces applied to RF and RH counterbalanced the moment of the body weight.

As the climber was in the process of releasing a limb, force variations were observed along each axis (Fig. 2). The net force began to change before the onset of the release (t_0) and did not present any statistical difference between the axes (-140 ± 21, -142 ± 28 and -138 ± 18 ms along X, Y and Z axes). Each latency was negative which means that each force variation preceded the onset of the voluntary RF release. The results show that the force changes observed at LH occurred statistically ($P < 0.05$) earlier than the force changes observed at LF and RH (-140 ± 22 vs. -73 ± 15 and -68 ± 15 ms). No statistical difference was observed between the latencies at LF and RH.

In the tripedal equilibrium state (Table 1), vertical (***Fk***) and horizontal forces (***Fi*** and ***Fj***) applied to LH and LF increased significantly ($P < 0.05$). The vertical force applied to RH hold did not present any significant change, whereas the horizontal forces applied to RH decreasing down to values around zero (-1.7 N along the antero/posterior axis and 0.8 N along the lateral axis).

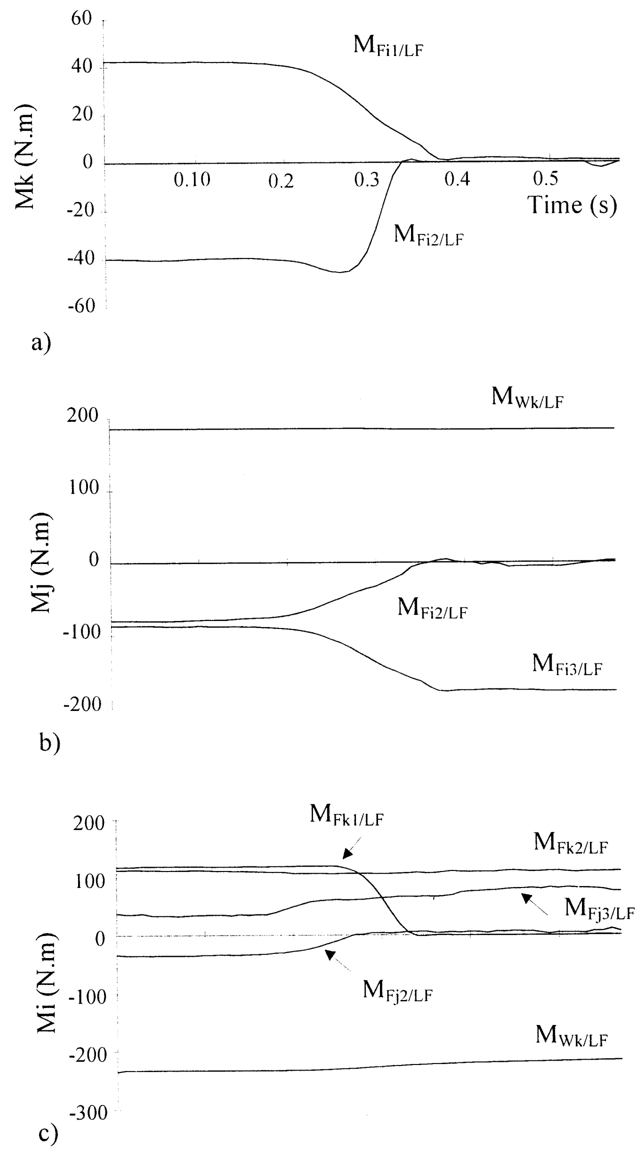

Fig. 3. Moment reactions computed from equation (3) around a) the vertical axis (Mk), b) the lateral axis (Mj) and c) the antero/posterior axis (Mi). Positive moments tend to rotate the climber counterclockwise, while negative moments tend to rotate the climber clock-wise.

Table 1
Mean forces magnitudes and standard deviation (N) in the four- and three-limb holds

	4-limb holds			3-limb holds		
	Fi	***Fj***	***Fk***	***Fi***	***Fj***	***Fk***
LH	−71 ± 21	−25 ± 7	187 ± 25	−127 ± 24*	−78 ± 17*	307 ± 60*
RH	−66 ± 18	24 ± 12	176 ± 20	−1.7 ± 0.2*	0.8 ± 1.8*	172 ± 27 n.s.
LF	71 ± 18	18 ± 11	180 ± 23	129 ± 16*	68.5 ± 15*	248 ± 42*
RF	62 ± 27	−18 ± 5	185 ± 20	–	–	–

* Represents a statistical difference.
n.s. represents no statistical variation between the 4-limb holds and the 3-limbs holds.

Table 2
Mean moment reactions and standard deviation (N.m)[a]

	4-limb holds			3-limb holds		
	Mi	***Mj***	***Mk***	***Mi***	***Mj***	***Mk***
LH	35 ± 17	99 ± 29	–	110 ± 26*	−178 ± 33*	–
RH	$F_{j2/LF}$ = −34 ± 13	92 ± 31	42 ± 14	$F_{j2/LF}$ = 5 ± 2.7*	−2 ± 2.21*	1 ± 0.1*
	$F_{k2/LF}$ = 112 ± 44	–	–	$F_{k2/LF}$ = 110 ± 18 n.s.	–	–
RF	118 ± 47	–	–	0*	–	0*
			40 ± 17			
W	−233 ± 32	189 ± 26	–	−226 ± 66 n.s.	191 ± 20 n.s.	–

[a] ***Mi***, ***Mj*** and ***Mk*** represent the moment reactions computed around the antero/posterior, lateral and vertical axis. ***Mi*** due to RH force was decomposed into two components ($M_{Fk2/LF}$ and $M_{Fj2/LF}$).
* Represents a statistical difference.
n.s. represents no statistical variation between 4- and 3-limb holds.

These reductions were both significant ($P < 0.05$). The magnitude of the moment reactions computed in the tripedal equilibrium state are reported in Table 2. Moments around the vertical axis (***Mk***) fell off significantly to around zero ($P < 0.05$). Around the lateral axis (***Mj***), the moment of the body weight remained quasi-constant (no significant change was observed). In fact, the displacement of the CG along the antero/posterior and lateral axes amounted to $X \pm Y$m. These low displacements induced no statistical body weight moment variation as presented in Fig. 3 and Table 2. RH moment decreased down significantly to around zero ($P < 0.05$), whereas the moment due to LH almost doubled ($P < 0.05$). Variations around the antero/posterior axis (***Mi***) showed that the body weight moment fluctuated around 3% and did not present any significant change. The magnitude of the moment due to the vertical force applied to RH did not present any significant change. It amounted to 112 ± 44 N.m before the hold release and to 110 ± 18 N.m after the hold release. Data show that the moment induced by the lateral force applied to the RH fell off significantly to around zero ($P < 0.05$), whereas the moment induced by the lateral force applied to LH shifted significantly ($P < 0.05$) from 35 ± 17 N.m to 110 ± 26 N.m.

4. Discussion

This work shows that when a hold is removed, the body balance requires a specifically organized arrangement of supporting forces. After the hold has been voluntarily released, the horizontal forces applied to the ipsilateral support decrease down to zero and increase as well onto the contralateral supports in order to restore translational and rotational equilibrium. At the same time, the vertical forces, which correspond to the body weight in static conditions, remain displayed on the three remaining holds. More precisely, the unique solution to restore rotation equilibrium around the vertical axis consists in decreasing the antero/posterior force applied to the right hand hold. Moreover, the center of gravity is quasi-unmoved which induced that the moment of the body weight around the lateral and antero/posterior axes remains constant. Consequently, the only solution to counteract this moment is to increase the antero/posterior force applied to the left hand hold. It is thus necessary to increase the antero/posterior force applied to LF in order to restore the translation equilibrium along the antero/posterior axis. Around the antero/poterior axis, the climber tends to rotate clock-wise unless he produces important opposite reaction forces. In order to reduce this phenomenon, the lateral force applied to the right hand falls off to zero and is applied to the left hand. This induces the decrease of the clock-wise moment due to the right hand force, and the increase of the counterclock-wise moment due to the left hand force. The steadiness of the vertical force applied to the right hand is probably due to the fact that increasing the vertical force and decreasing at the same time the horizontal forces applied to the same hold is a complex task [17].

It is interesting to mention that the subjects maintain the same position in the quadrupedal and tripedal state. In that case, the body weight moment is unchanged. The climber might have chosen a new position, which would have induced other mechanical constraints, and different supporting forces. Similar findings were reached in a horizontal quadrupedal position between a human (or a cat) and a rigged four-dropped ledge table [18]. Both behaved similarly when one of the four supporting trays is dropped. The authors [18] noted that the subject (cat or human) adopted a new position in the tripedal state after training sessions only. They concluded that maintaining the same initial position in the tripedal state was the easier choice for the central nervous system (the CG was not displaced), which probably results in less energy expenditure. Despite the fact that this explanation might be proposed in rock climbing, current data does not lead us to any conclusions. It would be conceivable to test tripedal stabilization after training. We can assume that the climber will adopt a tripedal position in which the moment of the body weight are reduced. Moreover, the dynamics of the reaction supporting force changes seem to suggest that the climber does not behave just as a rigid object and that the contributions of each of the remaining limbs to the support changes are not equal. A hierarchy seems to exist in the way postural adjustment associated with movement is organized [12,17].

In conclusion, this study shows that a model based on the principles of Newtonian mechanics specific to static equilibrium accurately describes the postural strategy of the climber and allows an understanding of the observed force changes in rock climbing. However, before conclusions can be drawn, more data must be collected and dynamically analyzed, using other climbing movements, such as hold reaching, and other positions, like when climbing a wall at different angles.

Appendix A. Nomenclature

RH	right hand
LH	left hand
RF	right foot
LF	left foot
(LF, $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$)	laboratory reference system
t_{Q}	time of quadrupedal stabilization
t_{APA}	time of first force change
t_0	time of onset of the right foot release
t_1	time of tripedal stabilization
CG	center of gravity of the climber
I	moment of inertia of the climber
$\boldsymbol{\alpha}$	angular acceleration of the CG
$\boldsymbol{a}$	linear acceleration of the CG
W	body weight (N)
$\boldsymbol{Fi}$	antero/posterior force vector
$\boldsymbol{Fj}$	lateral force vector
$\boldsymbol{Fk}$	vertical force vector
$M\boldsymbol{i}$	moment vector about the antero/posterior axis
$M\boldsymbol{j}$	moment vector about the lateral axis
$M\boldsymbol{k}$	moment vector about the vertical axis
$M_{\mathrm{F2}\boldsymbol{i}/\mathrm{LF}}$	moment vector due to the antero/posterior force F2 with respect to the LF (the same abbreviations are used for each moment)
$X_{\mathrm{CG}}(t_{\mathrm{Q}})$	initial position of the CG in the x-axis
$Y_{\mathrm{CG}}(t_{\mathrm{Q}})$	initial position of the CG in the y-axis
$X_{\mathrm{CG}}(t)$	position of the CG in the x-axis against time
$Y_{\mathrm{CG}}(t)$	position of the CG in the y-axis against time

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