3D ANALYSIS OF THE BODY CENTRE OF MASS IN ROCK CLIMBING

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The purposes of this study were: to test an experimental protocol for the analysis of basic rock climbing movements; to find whether it is possible to identify a golden standard strategy for the proposed movements. 12 recreational climbers were involved in the study. Each subject climbed a 3m horizontal shift followed by a 3m ascent. Climbers could choose their own style, their preferred speed and holds. Acquisition were performed using an optoelectronic system with reflective passive markers, attached to the subjects' joints. Results show that two main climbing strategies can be identified: the first preferring agility over force and the second preferring force over agility; we also found out that, good climbers try to minimize power, during the whole trial. These results would be our starting point for new experimental sessions.

KEY WORDS: rock climbing, center of mass, 3D analysis,.

INTRODUCTION: The practice of rock climbing is spreading in the last few years, at least in Italy: for the Italian Alpine Club, the growth of this sport was more than 200% in less than ten years and 118 climbing instructors taught about 3 courses/year (CAI web site, 2006); the Italian Climbing Federation (FASI) has more than 8000 athletes with a growth of 10% every year (FASI web site, 2006). Along with this quick development, questions come out about safety and equipment, but also about biomechanics, movement strategies and learning capacity.

By a review of the scientific literature, we found only a few authors dealing with the analysis of rock climbing movements: Bourdin (1998) worked on the organization of reaching and grasping movements due to the high postural constraints induced by rock climbing; Quaine (1997 and 1999) dealt with equilibrium tasks, but only for a single movement; a few authors (Rohrbough, 2000; Peters, 2001; Klauser, 2002 for example) focused their studies on the most frequent injuries in climbers; Boschker (2002) recorded the climbers with a video camera, to analyse observational learning strategies. All cited studies, except Boschker's, were performed on elite climbers.

We decided to analyse (using a 3D optoelectronic system and reflective passive markers) two basic rock climbing movements in a group of recreational climbers: a horizontal 3m shift followed by a 3m ascent, in a controlled environment offered by an indoor artificial wall.

Our main aims were: 1) to test our experimental protocol, 2) to find whether it is possible to identify a golden standard strategy for the proposed basic movements, 3) to search for common patterns in a group of climbers.

METHOD:

Data Collection: 12 recreational climbers underwent our experiment. Their mean age was 30.6 years (range: 16.2-49 years); the mean height was 1.74 m (s.d. 0.11 m) and the mean weight was 64 kg (s.d. 14.96 kg). The climbers signed an informed consent after the experimental protocol was fully explained to them. They also completed a questionnaire with their anthropometric data and their climbing experience: in particular we were interested in how long they have been practising rock climbing (1 month to 25 years) and which was their best performance in terms of route difficulty (4b to 7b, French scale).

Trials were performed on a vertical wall with holds of different shapes, orientations and dimensions. Each subject had to climb five times a 3 m horizontal shift followed by a 3 m ascent at his preferred technique and speed; there were no obliged hangs. A pause of 30 s was allowed between repetitions. All subjects completed the whole experimental session.

Climbing movements were recorded using an optoelectronic system (SMART3D^{TM}, BTS, Milan, Italy) with 6 infrared cameras (acquisition frequency 60 Hz), acquiring 12 reflective passive markers. Markers were positioned on the climber's joints (wrists, elbows, shoulders, hips, knees, ankles), as shown in Figure 1.

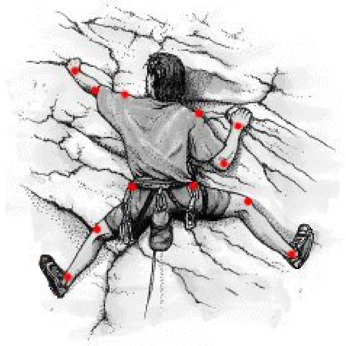

Figure 1: markers (in red) on the climber's joints

The calibrated volume was 5.06x3.41x1.98 m^3 (X, Y and Z direction respectively). An example of the reconstructed movement can be viewed in Figure 2, along with the calibrated volume (in green) and the calculated body centre of mass (magenta).

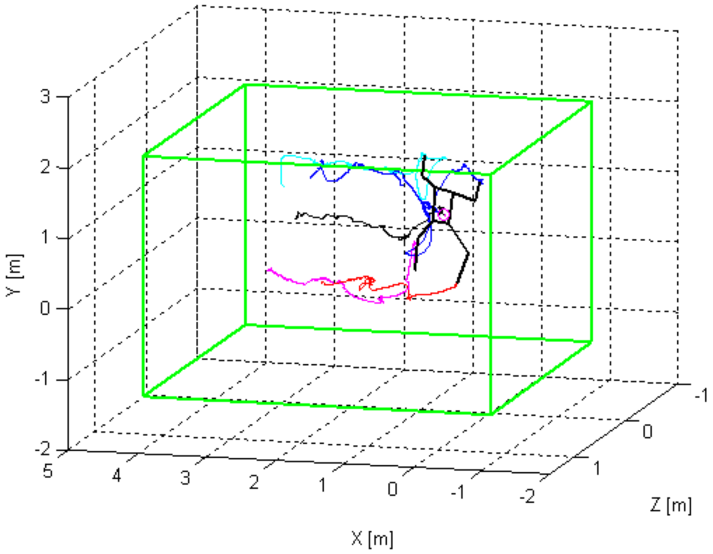

Figure 2: example of reconstructed climbing movement; calibrated volume (green), body centre of mass (magenta)

Data Analysis: the three-dimensional time coordinates (X, Y and Z) of each marker were reconstructed for each acquisition. The centre of mass trajectory of each climber was calculated by computing the mean of the centres of mass of the nine considered segments (trunk and head, arms, forearms, thighs, legs); the centre of mass of each segment was calculated from the markers coordinates, using the inertial parameters suggested by de Leva (1996). From the centre of mass coordinates (X, Y, Z), different parameters were computed: the geometric entropy on XY, XZ and YZ plane ($H = \ln(2LP/c)$, where *LP* is the pattern length of the centre of mass in the considered plane and *c* is the perimeter of the convex hull of *LP*); the absolute velocity value ($|V| = \sqrt{\dot{X}^2 + \dot{Y}^2 + \dot{Z}^2}$) ; the absolute acceleration value ($|A| = \sqrt{\ddot{X}^2 + \ddot{Y}^2 + \ddot{Z}^2}$); the power of acceleration signal ($P = \sqrt{(\int dsp(\ddot{X})df)^2 + (\int dsp(\ddot{Y})df)^2 + (\int dsp(\ddot{Z})df)^2}$), where *dsp* is the power spectral density of the acceleration signal.

Based on the position and speed of hands and feet markers, we also measured the mean number of holds per frame (with its standard deviation) for each climber. Correlation coefficient *r*, was calculated to find relationships between the computed parameters, then Student's *t-test* was applied (with threshold $p<0.05$) to verify the null hypothesis $r=0$ (tested parameters are not related). Data analysis was done using Matlab (The Mathworks Inc., Natick, MA, USA) custom functions.

RESULTS: Results are presented in deeper details for climber #4 and climber #6, because they clearly showed opposite climbing strategies.

In the whole group the mean number of holds per frame is 3.00±0.22; 6 out of 12 climbers use more than 3 holds per frame (mean) in all their trials. Climber #4 used 3.05±0.02 holds per frame, while climber #6 used 2.82±0.19 holds per frame.
Geometric entropy shows interesting results in all planes. In Table 1, the mean value (s.d.) of the whole group and the mean values (s.d.) for climber #4 and climber #6 are shown.

Table 1 Geometric entropy for plane XY, XZ and YZ

	Group mean (s.d.)	Climber #4 mean (s.d.)	Climber #6 mean (s.d.)
H (XY)	0.3486 (0.1859)	0.1456 (0.1095)	0.4089 (0.0492)
H (XZ)	0.4078 (0.2070)	0.1932 (0.1370)	0.5060 (0.0636)
H (YZ)	1.9717 (0.5088)	1.3902 (0.5784)	2.0822 (0.1747)

The mean absolute velocity for the whole group is |V|=0.2±0.12 m/s; climber #4 (0.17±0.09 m/s) is more regular and slower, than climber #6 (0.24±0.12 m/s).
The mean absolute value of acceleration for the whole group is |A|=1.39±1.28 m/s^2; at opposite sides we found climber #4 (1.02±0.96 m/s^2) and climber #6 showing higher and more sparse values (1.56±1.67 m/s^2).
The mean power *P* for the whole group is 0.34±0.17 m^2/s^4. The values of power show that climber #4 climbs 'at minimum power', with a mean value of 0.20±0.03 m^2/s^4, while climber #6 has got a higher mean value of 0.48±0.12 m^2/s^4 and also a higher standard deviation.
Correlation coefficients *r*, r^2 (percentage of variance in common between parameter #1 and parameter #2) and *p*-values for interesting couples of parameters are shown in Table 2; the coefficients are calculated taking into account the whole group of subjects.

Table 2 Correlation coefficients and *p*-values

Parameter #1	Parameter #2	r	r2	P
Mean hangs per frame	Mean |V|	-0.87281	76.18%	5.5217e-005
Mean |V|	Power	0.72572	52.67%	1.0532e-004
Mean |A|	Power	0.78002	60.843%	1.3081e-005

DISCUSSION: The inverse correlation between mean holds per frame and mean velocity is easy to explain: if the climber uses a smaller number of holds to move along the wall, he has to be quick enough to maintain the equilibrium; vice versa if the number of holds is equal or greater than 3, it is more likely that the subject can climb slowly, because his equilibrium is always under control. Climber #4 and climber #6 show opposite styles: the first moves more slowly and uses a greater number of holds per frame, the second is quicker and uses a smaller number of hangs per frames.

When it comes to geometric entropy, the difference between climber #4 and climber #6 remains great, the first being far below the group mean and the second being above. Since geometric entropy is a measure of fluency, we can conclude that climber #4 is less chaotic, more fluent, in the movement than climber #6. These results agree with those of Boschker (2002), who found that the lower the geometric entropy, the higher the climbing performance.
From Newton's law we can deduce that, the mean acceleration is an index of the mean global force used during the movement. Climber #4 and climber #6 show again opposite

styles: the first shows a mean value well below the group mean and a small standard deviation, while the second shows a greater value as compared to the group mean and a higher standard deviation. A small standard deviation value is also a sign of good repeatability: climber #4 shows more regular values between the trials than climber #6.
Power values confirm the results of acceleration values; the two climbers show again opposite strategies, climber #4 moves with more agility and technique than power, the opposite for climber #6, who uses more power and force than agility and technique.
Qualitative analysis of the climbing styles adopted by climbers #4 and #6 confirms the numerical results reported here. Climber #4, which climbs up to 7b, moves naturally onto the rock wall, linking together a series of fluid movements; on the other hand, climber #6, which climbs up to 6b, executes a set of quick movements, using brute force to advance through the rock wall.

CONCLUSION: This pilot study identified the behaviour of the body centre of mass in rock climbing. The presented experimental protocol seems suitable for the analysis of kinematics in rock climbing. The evaluated parameters demonstrate the existence of two major strategies: the first (subject #4) refers to 'agility' and seems to require less speed and less power for the movement to be successfully completed, the second (subject #6) refers to 'power' and requires more speed and more force for the movement to be successfully completed. We think that climber #4 strategy could be the more effective, thus, summarizing, our results show that a good climber tries to minimize both geometric entropy and power during the whole trial. Our data do not permit to conclude that this conclusion represents a golden standard strategy, however this hypothesis constitutes a starting point for future experimental sessions. However, all the calculated parameters could be interesting for future comparisons with different groups of climbers (elite athletes, beginners, children,...). At the end, we did not find common patterns in the analysed group, but it is probably due to the fact that our group was not homogeneous enough.

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