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SEIFERT, Ludovic, ORTH, Dominic, BOULANGER, Jérémie, DOVGALECS, Vladislavs, HÉRAULT, Romain and DAVIDS, Keith <http://orcid.org/0000-0003-1398-6123>

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Climbing skill and complexity of climbing wall design: Assessment of Jerk as a novel indicator of performance fluency. Journal of Applied Biomechanics

Ludovic Seifert[1], Dominic Orth[1,2], Jérémie Boulanger[1], Vladislavs Dovgalecs[1], Romain Hérault[3], Keith Davids[4,5]

[1] CETAPS - EA 3832, Faculty of Sport Sciences, University of Rouen, France

[2]School of Exercise & Nutrition Science, Queensland University of Technology, Brisbane, Australia

[3] LITIS - EA 4108, National Institute of Applied Sciences (INSA), Rouen, France

[4] Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, United Kingdom

[5]FiDiPro Programme, University of Jyväskylä, Finland

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Corresponding author: Ludovic SEIFERT, Faculty of Sports Sciences, CETAPS, University of Rouen, Boulevard Siegfried, 76821 MONT SAINT AIGNAN cedex, FRANCE, @: ludovic.seifert@univ-rouen.fr, Tel : (+33) 235147784, Fax : (+33) 232107793

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Abstract

This study investigated a new performance indicator to assess climbing fluency (smoothness of the hip trajectory and orientation of a climber using normalized jerk coefficients) in order to explore effects of practice and hold design on performance. Eight experienced climbers completed 4 repetitions of two, 10-m high routes with similar difficulty levels, but varying in hold graspability (holds with one edge *vs.* holds with two edges). An inertial measurement unit was attached to the hips of each climber to collect 3D acceleration and 3D orientation data in order to compute jerk coefficients. Results showed high correlations (r = .99, P<.05) between the normalized jerk coefficient of hip trajectory and orientation. Results showed higher normalized jerk coefficients for the route with two graspable edges, perhaps due to more complex route finding and action regulation behaviours. This effect decreased with practice. Jerk coefficient of hip trajectory and orientation could be a useful indicator of climbing fluency for coaches as its computation takes into account both spatial and temporal parameters, i.e., changes in both climbing trajectory and time to travel this trajectory.

Key words: Movement jerk, climbing fluency, hold design, inertial measurement unit.

Introduction

Rock climbing involves interspersed periods of maintaining body equilibrium on a more or less vertical climbing surface[1–4], with combining upper and lower limb movements to ascend this surface rapidly.[5–7] During performance, the alternation of periods dedicated to postural regulation and to quadruped displacement on a vertical surface, might lead to a drop in measures of climbing fluency that is fundamental to quantify. Previous studies have assessed the fluency of climbing movements from temporal and spatial measurement analyses.

Temporal measurement analyses have included harmonic analysis of the acceleration of the hips[8] and quantification of the duration of a static position as any point throughout the climb where the hips were not in motion.[9–11] Harmonic analysis is a tool for observing the structure of movement dynamics. Using Fourier transformation, Cordier et al.[8] conducted a harmonic analysis revealing that the expert climbing performance could be characterized by a pendulum oscillating as a mass-spring system that works like a dissipative system, i.e., a system where dissipation of energy is minimized by harmonic movements. The study of Cordier et al.[8] only considered the displacement of the hips in 2D (i.e., movement projection in the vertical plane), whereas recent studies have highlighted the prevalence of antero-posterior and lateral sway during climbing performance[7,12], supporting the importance of 3D movement analysis, which should take into account both hip translation and hip rotation.

Spatial measurement analyses mainly corresponded to computations of the geometric entropy index value from the displacement of the hips.[7,13–16] The geometric index of entropy (H) was calculated by recording the distance path covered by the hips (L) and the perimeter of the convex hull around that path (c) according to the following equation[14,15]:

$H = \log_n 2L/c$ (equation 1)

According to Cordier et al.[14,15] geometric entropy measures reveal the amount of fluency/curvature of a curve: the higher the entropy, the higher the disorder of the system; therefore, a low entropy value was associated with a low energy expenditure and greater climbing fluency. Regardless, the geometric entropy index remains a spatial measure of body motion that does not consider the displacement of the hips over time, only the image of their trajectory. Entropy measures do not consider the way that this trajectory is achieved. Therefore, when a climber pauses for the purposes of route finding or for postural regulation, it is not taken into consideration by the geometric entropy index. Therefore, it is necessary to develop an indicator of climbing fluency that considers both spatial and temporal measurements.

A previous study exploring self-handicap factors on successful climbing performance highlighted that competitive climbers exhibited "*performance anxiety through rigid posture and jerky movements which could limit performance by reducing movement fluency*" (pp.276).[17] This study led us to seek the best way to assess climbing fluency from computation of jerk values. Previous research in domains other than sport climbing has revealed that the jerk coefficient (i.e., third time derivative of position or the rate of change of acceleration) is a valid indicator of the smoothness of trajectory during multi-joint limb motion.[18,19] An assumption in these previous studies is that maximizing arm movement smoothness may be modelled by minimizing the mean-square jerk, reducing energy cost. The validity of this jerk minimisation hypothesis has been investigated in various tasks involving upper-limb movements such as pointing[20,21], throwing[22], reaching[23] and drawing[24], as well as in lower-limb tasks such as walking[25] and kicking.[26]Only one previous study has attempted to compute jerk in climbing to assess performance fluidity; however, only 3D acceleration values from sensors were used in that analysis, which did not obtaining jerk values in an Earth frame of reference.[27] Another limitation of that study was the use of ear-worn sensors for performance measurement, despite the fact that the head is known to be highly mobile in climbing;

The main aim of this study was to examine whether the computation of jerk coefficient values could provide an indicator of climbing fluency. In fact, as suggested previously, climbing fluency could be defined as the smoothness of the 3D translations and 3D rotations of the hips, which invited us to compute the jerk of hip trajectory and hip orientation, and examining their relationship. A good method to check the utility of computing the jerk for hip orientation is to manipulate the design of a climbing. Previous work has found that horizontal edge hold grasping can lead to the adoption of a 'face-to-the-wall' body orientation, whereas vertical edge hold grasping can induce a 'side-to-the-wall' body orientation.[28] Therefore, by designing a climbing route with vertical edge holds, we expected to observe hip rotation during climbing, from which climbing fluency could be assessed through jerk of hip orientation. Moreover, when a complex route is designed with holds offering *dual* edge orientations (combining horizontal and vertical edges), climbers may explore two types of grasping patterns and body orientations[28], that may lead to observation of higher jerk values. Therefore, a second aim for us was to investigate whether jerk may be influenced by climbing wall design (simple *vs.* complex hold grasping patterns), and whether it might change with practice. We hypothesized that jerk coefficients of hip trajectory and orientation are likely to be correlated, lower in value for simple hold design routes and decrease with practice.

Methods

Participants

Eight students of a Faculty of Sport Sciences voluntary participated to this study (mean age: 21.4 ± 2.4 yr; mean height: 170.1 ± 9.5 cm; mean weight: 69.9 ± 5.5 kg). These climbers had climbing experience of 4.1 ± 2.1 yr, trained for 3.4 ± 1.9 hours per week and had a rock climbing ability of 6a on the French Rating Scale of Difficulty (F-RSD)[29], which corresponds to an intermediate level of performance.[30] Climbing ability was defined as the most difficult ascent by top rope.[29]

Protocol

Each climber participated in four testing sessions (separated by two days of rest), each consisting of two different route ascents. Participants were randomly allocated to climb two routes of a similar grade rated 5c on the F-RSD in top-roped condition. Each route was identifiable by colour and was set on an artificial indoor climbing wall by two certified route setters who ensured that they matched intermediate climbing levels. The routes had the same height (10m) and were composed of 20 hand holds each, located at the same place on the artificial wall. Only the orientation of the hold was changed between the two routes: the first route was simply designed to allow horizontal edge hold grasping, while the second route was designed more complexly to allow both horizontal and vertical edges hold grasping (Figure 1). This design allowed us to examine whether the level of grasping uncertainty could constrain climbing fluency. Participants were instructed to self-pace their ascent, to climb fluently and to climb without falling. Each ascent was preceded by 3 minutes of route preview, as pre-ascent visual inspection is a key climbing performance parameter.[10] The protocol was approved by the local University ethics committee and followed the declaration of Helsinki. Procedures were explained to the climbers, who then gave their written informed consent to participate.

Insert figure 1

Data collection

The original feature of our study was to collect body acceleration and orientation data from an IMU located at the hip, in order to compute jerk. Previous studies have used piezoelectric accelerometers for this purpose[31,32] or ear-worn accelerometer sensors.[27] In our study, an IMU corresponded to a combination of a tri-axial accelerometer (±8G), tri-axial gyroscope (1600°.s^{-1}) and a tri-axial magnetometer (*MotionPod*, Movea©, Grenoble, France). Data collected from the IMU (with *MotionDevTool*, Movea©, Grenoble, France) were recorded with North magnetic reference and at a 100 Hz sample frequency.

Data analysis

The first step towards computation of jerk coefficients was to compute hips orientation in the Earth reference frame and follow its orientation changes. Raw accelerometer readings cannot be used directly to compute the jerk coefficient due to orientation changes during ascent. The solution to this problem was found by tracking sensor orientation by using the complementary filter based algorithm[33,34], which integrated the three sensor information sources (i.e., accelerometer, gyroscope and magnetometer). The gyroscope measured precise angular changes at very short time durations but could not be used to track the angle changes by integration due to a drift issue. The accelerometer provided absolute, albeit noisy, measurements of hip acceleration and the Earth's gravitational force at the same time. By combining the two sensor information sources it was possible to reduce drift of the gyroscope for hip orientation tracking. When magnetometer information was added, it was possible to compute orientation of the sensor with respect to the fixed frame of Earth reference (magnetic north, East and gravity directions).[33,34]

Second, the accelerometer readings were always expressed with respect to the sensor frame and it was necessary to separate hip acceleration, of interest for jerk computation, and the constant acceleration of gravity. Let $R_t \in SO(3)$ be the current sensor orientation at time t in the Earth frame of reference, a_t^{SF} the measured acceleration of the hips in the sensor frame, then the acceleration of the hips at time t in the fixed Earth reference frame can be expressed as:

$$a_t^{GF} = R_t a_t^{SF} \qquad \text{(equation 2)}$$

The third step consisted of assessing smoothness of the hips trajectory by computing the jerk coefficient from processed 3D accelerometer signals a_t^{GF}. Jerk is a measure of the lack of smoothness of a joint or limb trajectory during performance. For a smooth trajectory $x^{GF} \in C^3([O,T])$, the jerk $J_{x^{GF}}$ was defined as:

$$J_{x^{GF}}(T) = C \int_0^T \left\| \dddot{x}_s^{GF} \right\|^2 ds \qquad \text{(equation 3)}$$

Where C was a normalization constant to make the quantity dimensionless.[35] In practice instead of computing x_t^{GF} (position on the wall) from a_t^{GF} with successive integration, the term $\dddot{x}_s^{GF}$ was replaced by $\dot{a}_t^{GF}$. By derivation of a_t^{GF}, the constant gravity acceleration was removed, letting only the hip acceleration component.

It is noteworthy that the jerk was minimized when x_t^{GF} is a fifth degree polynomial, corresponding to the smoothest possible hip trajectory. The integral was computed between time 0 and time T which corresponded to a given final position x_T^{GF}. The constant C can be chosen such that:

$$C = \frac{T^5}{(\Delta x^{GF})^2} \qquad \text{(equation 4)}$$

Where Δx^{GF} was the climbing height and T the time needed to reach it. It should also be noted that the current position x_t^{GF} was not available from IMU sensor data and, therefore, jerk could be computed for an arbitrary position interval. The only height information was the total height of the ascent; therefore, the jerk coefficient could be computed for the whole ascent but not for a local displacement path. Thus, the normalized jerk coefficient was computed by differentiating the processed accelerometer signal and integrating its squared norm.

A second indicator of climbing fluency consisted of computing jerk coefficient measuring hip orientation smoothness. Indeed, as stated previously, hip displacements of climbers not only correspond to 3D translations, but also to 3D orientations.[7,8,12] These results highlighted the interest of studying jerk now defined from hip orientation $R_t \in SO(3)$. In this case the previous equation could not be used directly and some technical adjustments were required. Due to the structure of $SO(3)$, orientation acceleration could not be obtained by directly considering successive derivation of R_t as a 3x3 matrix.The solution to this problem in our study consisted of constructing a process $z_t \in \mathbb{R}^3$ such that its velocity was the angular velocity of R_t, which can be differentiated easily (note that z_t and R_t are of the same dimensionality). We define z_t as:

$$\dot{z}_t = \dot{R}_t R_t^{-1} \qquad \text{(equation 5)}$$

Where $R_t^{-1} = R_t^T$, due to the orthogonality of the elements of $SO(3)$. If R_t has an angular velocity ω_t, then $\dot{z}_t = \omega_t$. Therefore, working on z_t allowed us to eliminate all the non-linear issues inherent to $SO(3)$ and work in $\mathbb{R}^3$ instead, where derivative was carried out simpler than in $SO(3)$. In practice, due to the discretization of observations of R_t with a sampling time δt, the process z_t was approximated by $\widetilde{z_k} \approx z_{k\delta t}$, with $\tilde{z}$ recursively computed as:

$$\widetilde{z_{k+1}} - \widetilde{z_k} = log\left(R_{(k+1)\delta t} R_{k\delta t}^{-1}\right) \qquad \text{(equation 6)}$$

Where log was the inverse application of the matrix exponential. In our study, jerk of orientation was defined as $J_z(T)$.

Statistical analysis

After the computation of the jerk from z_t for each session, differences of jerk coefficients between sessions and route designs were compared by two-way repeated measures ANOVA (practice across four sessions and climbing wall design across two different routes) using SPSS Statistics 20.0. Sphericity was verified by the Mauchly test.[36] When the assumption of sphericity was not met, the significance levels of F-ratios were adjusted according to the Greenhouse-Geisser procedure. Then, Helmert contrast tests enabled us to compare each session with the jerk mean of the other sessions, in order to determine whether jerk reduced with practice and whether route design influenced jerk values. Here it was predicted that routes providing double edges (vertical and horizontal) grasping patterns would be associated with more jerk compared to the route where only horizontal grasping was afforded. Partial eta squared (η_P^2) statistics were calculated as an indicator of effect size, considering that $\eta_P^2 = 0.01$ represents a small effect, $\eta_P^2 = 0.06$ represents a medium effect and $\eta_P^2 = 0.15$ represents a large effect.[37] Pearson correlation tests were also performed to examine the relationships between jerk of hip trajectory $J_x(T)$ and jerk of hip orientation $J_z(T)$. For all tests, the level of significance was fixed at $P<.05$.

Results

Significantly higher values of normalized jerk for hip trajectory emerged in the double edges holds route in comparison to the horizontal edge holds route ($41.08\times 10^6 \pm 2.18\times 10^6$ *vs.* $8.17\times 10^6 \pm 0.46\times 10^6$; $F_{1,7} = 6.14$, $P = .03$, $\eta_P^2 = 0.463$). Similar results were observed for normalized jerk of hip orientation; this latter measure was higher for the double edges holds route in comparison to horizontal edge holds route (7767 ± 434 *vs.* 1555 ± 96; $F_{1,7} = 6.22$, $P = .028$, $\eta_P^2 = 0.442$).

For session effect, Mauchly's test indicated significant sphericity ($\chi 2$ (5) = 38.55, $P = .01$), so the Greenhouse-Geisser correction was applied and showed significant differences of normalized jerk of hip trajectory between sessions (session 1: $68.65\times 10^6 \pm 3.78\times 10^6$, session 2: $21.23\times 10^6 \pm 1.33\times 10^6$, session 3: $4.61\times 10^6 \pm 0.14\times 10^6$, session 4: $4.02\times 10^6 \pm 0.13\times 10^6$; $F_{1.05,7.348} = 5.18$, $P = .034$, $\eta_P^2 = 0.428$). According to the outcomes of the

Helmert contrast tests, significant differences occurred between the first session and the others ($F_{1,7}$ = 5.14, P = .038, η_P^2 = 0.424), and between the second session and the last two sessions ($F_{1,7}$ = 5.08, P = .041, η_P^2 = 0.413). Mauchly's test indicated significant sphericity ($\chi 2$ (5) = 64.94, P = .01) when differences of normalized jerk of hip orientation were analysed between sessions. Thus, the Greenhouse-Geisser correction was applied, revealing significant differences between sessions (session 1: 13147 ± 575, session 2: 4147 ± 244, session 3: 726 ± 19, session 4: 626 ± 18; $F_{1.013,7.092}$ = 5.34, P = .027, η_P^2 = 0.436). According to the Helmert contrast tests, significant differences emerged between the first session and the others ($F_{1,7}$ = 5.27, P = .032, η_P^2 = 0.428), and between the second session and the last two sessions ($F_{1,7}$ = 5.18, P = .034, η_P^2 = 0.417). Figure 2 illustrates the differences of normalized jerk of hip trajectory between sessions for the two routes and Figure 3 illustrates the differences of normalized jerk of hip orientation between sessions for the two routes.

Insert figures 2 and 3

A significant positive correlation appears between the normalized jerk of hips trajectory and normalized jerk of hips orientation (r = .99, P<.001) (Figure 4). This finding signifies that both measures provide a similar measure of smoothness, the only difference being the scale of the two coefficients.

Insert figure 4

Discussion

Translations and rotations of the hips correspond to two independent components of the 3D motions of the trunk during climbing performance. However, our results demonstrated high correlation values between the normalized jerk values of hip trajectory and hip orientation revealing that both 3D translations and 3D rotations of the hips should be considered to assess climbing fluency. This correlation might be lower in beginners who mainly climb with a 'face-to-the-wall' body orientation. Our results confirmed the limitations of using 2D spatial analysis (by projecting the hip trajectory on the plane of the climbing wall)[7] and by using only a spatial measurement, as previously undertaken through the geometric entropy index.[10,14,15] Indeed, climbers can exhibit saccades (variations in speed) of hip displacement when they explore hold grasping[7,38], as well as longer pauses dedicated to the tasks of active resting[39], route finding[14,15]and postural regulation[1–3], which invite consideration of temporal measurements to assess fluency of climbing performance. Thus, jerk coefficients of hip trajectory and hip orientation offer valuable indicators of climbing fluency because they include consideration of spatial-temporal 3D translation and 3D rotation of the hips.

Our results showed that the normalized jerk values of hip trajectory and orientation were lower for the simple route design (i.e., horizontal edge holds grasping). In fact, climbing a route with horizontal edge holds resembled the action of grasping the rungs of a ladder, explaining how lower normalized jerk values of both hip trajectory and orientation emerged in the simple route than rather the complex route. Horizontal edge hold grasping led to the adoption of a 'face-to-the-wall' body orientation, whereas vertical edge hold grasping induced a 'side-to-the-wall' body orientation.[28] Therefore, the complex route design, with holds offering dual edge orientations, invited climbers to explore two types of grasping patterns and body orientations[28]. In fact, moving between a right-orientated vertical edge hold to a left-orientated vertical edge hold would lead the body to rotate as if on the hinges of a door, a performance feature particularly well captured by recording the jerk of hip orientation. With a ‘side-to-the-wall’ body orientation, a high value of jerk for hip orientation is observed, and because the axis of rotation is not the trunk, but passes through hands and feet, a higher jerk value in both 3D translations and 3D rotations of the hip emerged from this trunk position. Previous studies have already shown how route design influences the kinematics of climbers, highlighting the value of movement time during hold grasping[6] and the entropy measure of hip displacement.[16] More precisely, complexity of manual grips (2 cm *vs.* 1 cm depth) and posture difficulty (low *vs.* high angle of inclination of foot holds) led to shorter movement times for grasping; in particular, longer times to reach maximum acceleration, and shorter times to reach the maximum deceleration were observed.[6] Moreover, complex hold grasping and more difficult postures emerged occasionally during the route that corresponded to a 'crux' (i.e., most difficult section of the route) or all over the route.[40] In these studies, it has been reported that the crux led to the emergence of higher entropy values for hip displacement and higher movement times in skilled climbers than in less skilled individuals[16], supporting the utility of computing jerk as precisely as possible by taking into account values of both hip trajectory *and* orientation.

Our results showed a critical drop in observed values of jerk with practice, notably between the first and remaining three sessions, with stabilization emerging between the last two sessions. These results clarify contradictory data from previous studies that have analysed the effect of practice on jerk minimization.[26,41] When arm movements were trained at different speeds, Schneider and Zernicke[41] showed that jerk decreased for the slowest hand movement with practice. Conversely, when learning to kick, participants revealed different jerk values for movements with similar trajectories, which did not support the jerk minimization hypothesis with practice.[26] In our study, higher values of jerk for hip trajectory and orientation emerged in the first practice session, which could have been due to absence of prior knowledge of route finding that may have led to a search process in participants.[14]In fact, three different conditions of practice may influence climbing fluency: 'on-sight' climbing involves successful climbing with no prior knowledge of the climb; 'flash climbing' means successful climbing at the first attempt after receiving prior knowledge of the climb; 'red-point' climbing signifies successful climbing without falling after previous unsuccessful attempts.[40] These assumptions have been confirmed by a recent study that showed significant reductions in the number and duration of stops when climbing with a route preview.[10]To consider the possible effects of previewing on climbing fluency, three minutes of previewing were allowed in our study. However, route previewing does not appear to be the main constraint on emergence of climbing fluency. Improvement in route finding (i.e., interpretation of the ever-changing structure of the climbing wall design[15]) could further explain the drop of jerk values and the decrease in the number of exploratory movements with practice. Indeed, Cordier et al.[14,15]have already reported that practice can lead to less exploration during route finding and lower entropy values of hip displacement, imputing greater climbing fluency. To summarise, our study was able to propose a methodology of implementing an IMU during climbing to record jerk as a measure of climbing fluency involving the upper and lower limbs together. Assuming that the hips can perform 3D translation and 3D rotation during climbing, the computation of jerk values for hip trajectory and orientation provided two complementary indicators of climbing fluency that present a valuable contribution to understanding the effects of practice and route design on climbing performance.

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Figure captions

Figure 1. Orientation and shape of the holds for the two routes. The arrow indicates the preferential edge grasping allowed by the hold.

Figure 2. Differences of normalized jerk of hips trajectory between sessions for the complex route design (i.e., double edges holds route) (black line) and the simple route design (i.e., horizontal edge holds route) (dotted line).

Figure 3. Differences of normalized jerk of hips orientation between sessions for the complex route design (i.e., double edges holds route) (black line) and the simple route design (i.e., horizontal edge holds route) (dotted line).

Figure 4. Correlation between jerk of hips trajectory (x-axis) and jerk of hips orientation (y-axis) for the simple route design (4a) and the complex route design (4b).