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

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Abstract

This study investigated a new performance indicator to assess climbing fluency: smoothness and orientation of the hip trajectory of a climber using normalized jerk coefficients. To analyse performance fluency, 6 experienced climbers completed 4 repetitions of two 10-m high routes with similar difficulty levels, but varying in hold graspability (hold with one edge *vs.* hold with two edges). An inertial measurement unit was attached to the hip of each climber to collect 3D acceleration and 3D orientation data in order to compute jerk coefficients. Results showed high correlations ($r = 0.83$, $p<0.05$) between the normalized jerk coefficient of hip translation and hip oscillation. Results showed higher normalized jerk coefficients for the route with two graspable edges, perhaps due to more complex decision making and action regulation. This effect decreased with practice.

Key words: Movement jerk, climbing, hip translation, hip orientation, inertial measurement unit, fluency.

1. Introduction

Previous research has revealed that the jerk coefficient (third time derivative of position or the rate of change of acceleration) is a valid indicator of multi-joint limb movement smoothness (Flash and Hogan, 1985; Hogan, 1984). An assumption in this previous work is that maximizing arm movement smoothness may be modelled by minimizing the mean-square jerk, reducing energy cost. The validity of this minimizing jerk hypothesis has been investigated in various tasks involving upper-limb movements such as pointing (Goldvasser et al., 2001; Klein Breteler et al., 2002), throwing (Yan et al., 2000), reaching (Wininger et al., 2009) and drawing (Richardson and Flash, 2002), as well as d in lower-limb tasks such as walking (Young and Marteniuk, 1997) and kicking (Young and Marteniuk, 1997). Contrasting results have emerged, suggesting, for instance, that high curvature analysis was more convenient than jerk computation to distinguish healthy and cerebellopathy patients performing pointing tasks (Goldvasser et al., 2001). It was also observed that quantifying spontaneous accelerative transients within a movement when performing reaching tasks provided more reliable information on regional movement impairments than recording the jerk coefficient (Wininger et al., 2009).

The sport of rock climbing involves both upper and lower-limbs for reaching and grasping holds, and climbing up a rock surface with the feet. It is particularly valuable to assess the validity of the minimizing jerk hypothesis as a potential indicator of fluency in climbing performance. 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 (Ferrand et al., 2006). Rock climbing involves interspersed periods of maintaining body equilibrium on a more or less vertical climbing surface (Bourdin et al., 1999, 1998;

Testa et al., 2003, 1999), with combining upper and lower limb movements to ascend these surfaces rapidly (Boschker et al., 2002; Nougier et al., 1993; Sibella et al., 2007). 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 by: (i) implementing a harmonic analysis of the acceleration of the hips (Cordier et al., 1996), by quantifying the duration of a static position as any point throughout the climb where the hips were not in motion (Billat et al., 1995; Sanchez et al., 2012; Seifert et al., 2013b); and (ii), by measuring the geometric entropy index value from the displacement of the hips (Boschker and Bakker, 2002; Cordier et al., 1994, 1993; Sanchez et al., 2010; Sibella et al., 2007). Harmonic analysis is a tool for observing the structure of the dynamics of a movement. Using Fourier transformation, Cordier and colleagues (Cordier et al., 1996)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. Although very promising, the study of Cordier et al. (1996) 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 (Sibella et al., 2007; Zampagni et al., 2011), supporting the importance of 3D movement analysis. Similar limitations emerge from the use of the geometric entropy index, (Boschker and Bakker, 2002; Cordier et al., 1994, 1993; Sanchez et al., 2010; Sibella et al., 2007). The geometric index of entropy (H) was calculated by recording the distance covered by the body (L) and the convex hull (c) according to the following equation: $H = \log_n 2L/c$(Cordier et al., 1994, 1993). According to Cordier et al. (Cordier et al., 1994, 1993), 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, geometric entropy index remains a spatial analysis of the body motion that does not consider the displacement of the hips over time. This is an omission since both hip translations and oscillations in 3D should be considered to assess climbing fluency. The aim of this study was to explore whether the computation of jerk coefficient values could provide an indicator of climbing fluency, achieved by computing the jerk of hip trajectory and hip orientation and examining their correlation. We also sought to investigate whether jerk is minimized with practice and modifications to climbing wall design (simple *vs.* complex hold grasping patterns).

2. Methods

2.1. 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) (Delignières et al., 1993), which corresponds to an intermediate level of performance (Draper et al., 2011). Climbing ability was defined as the most difficult ascent by top rope (Delignières et al., 1993).

2.2. 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. 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 (10 m) 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 designed to allow horizontal edge hold grasping, while the second route was designed to allow both horizontal and vertical edges hold grasping (Fig. 1). This design allowed us to examine whether the level of grasping uncertainty could constrainclimbing fluency. Participants were instructed to self-pace their ascent, to climb fluently and to climb without falling. Each route was top-roped, i.e., routes were climbed with the rope anchored above the climber at all times. Each ascent wa preceded by 3 minutes of route preview, as pre-ascent visual inspection is a key climbing performance parameter (Sanchez et al., 2012). 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.

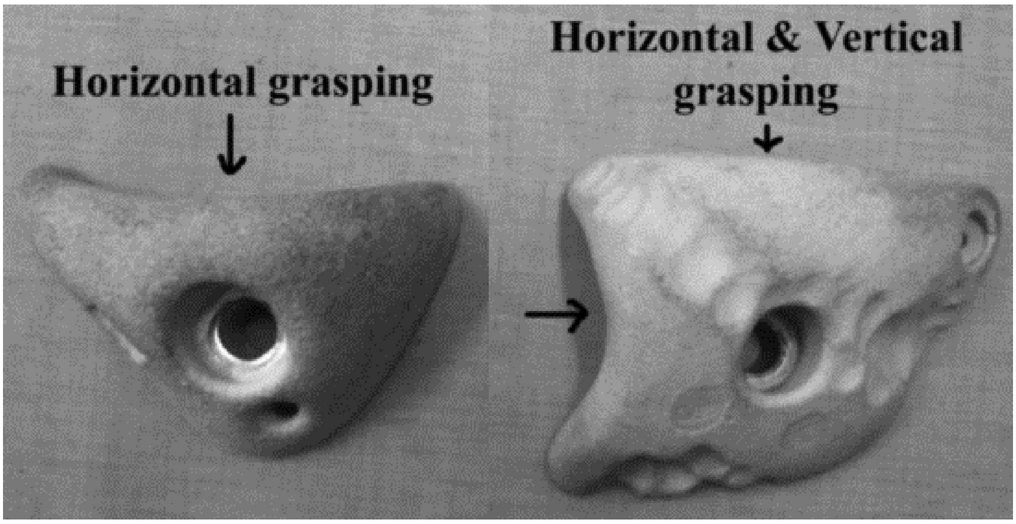

Figure 1. Orientation and shape of the holds for the two routes. The arrow indicates the preferential edge grasping allowed by the hold.

2.3. Data collection

In line with previous studies, climbing fluency was assessed through recording hip displacements (Cordier et al., 1994, 1993; Sanchez et al., 2010; Sibella et al., 2007). The original feature of our study was to collect body acceleration data from an IMU located at the hip, in order to compute jerk. Previous studies have used piezoelectric accelerometers for this purpose (Minami et al., 2011, 2010). 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.

2.4. Data collection and analysis methods

The first step towards computation of jerk coefficients was to compute hip orientation in 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 (Madgwick, 2010; Madgwick et al., 2011), 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 the problem of drift. 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) (Madgwick, 2010; Madgwick et al., 2011).

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 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 hip in the sensor frame, then the acceleration of hip at time t in the fixed Earth reference frame can be expressed as $a_t^{GF} = R_t a_t^{SF}$.

The third step consisted of assessing smoothness of the hip 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 segment during performance. For a smooth trajectory $x^{GF} \in C^3$, the jerk $J_{x^{GF}}(t)$ was defined as: $J_{x^{GF}}(T) = C \int_0^T \left\| \dddot{x}_s^{GF} \right\|^2 ds$ where C was a normalization constant to make the quantity dimensionless (Hogan and Sternad, 2009). 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, leaving 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 $C = \frac{T^5}{(\Delta x^{GF})^2}$, 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 orientation oscillations (Cordier et al., 1996; Sibella et al., 2007; Zampagni et al., 2011). 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 $\dot{z}_t = \dot{R}_t R_t^{-1}$ where $R_t^{-1} = R_t^T$ which is due to 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 $\widetilde{z_{k+1}} - \widetilde{z_k} = log\left(R_{(k+1)\delta t} R_{k\delta t}^{-1}\right)$ where log was the inverse application of the matrix exponential. In our study, jerk of orientation was defined as $J_z(T)$.

The last indicator computed in our study related to elucidating climbing skill of participants (e.g., the capability of traversing an ascent quickly) through differentiating the relationship between touched holds (exploratory movements) and grasped holds (performatory movements) (Pijpers et al., 2006). Indeed, Pijpers and colleagues (2006) distinguished exploratory and performatory movements according to whether a potential hold on a climbing wall was touched, with or without it being used as support. According to this ratio, Sibella et al. (2007) reported that skilled climbers can move quickly by using fewer than three holds, signifying that they had touched fewer than three surface holds before grasping the functional one.

2.5. *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 (4) and climbing wall design across two different routes (2)) using SPSS Statistics 20.0. Sphericity was verified by the Mauchly test (Winter et al., 2001). When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse-Geisser procedure. Then, Helmert contrast tests enabled us to compare each session with the performance 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 (Cohen, 1988). 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 $p < 0.05$.

3. 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 (4.48E+11 ± 1.77E+11 *vs.* 9.65E+10 ± 4.44E+10; $F_{1,7} = 6.14$, $p = 0.03$, $\eta_P^2 = 0.463$). 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 (776846 ± 434836 *vs.* 155590 ± 96743; $F_{1,7} = 6.22$, $p = 0.028$, $\eta_P^2 = 0.442$).

To examine session effect, Mauchly's test indicated significant sphericity ($\chi2$ (5) = 38.55, p = 0.01), so the Greenhouse-Geisser correction was applied and showed significant differences of normalized jerk of hip trajectory between sessions (session 1: ± 2.93E+11, session 2:

2.13E+11 ± 9.11E+10, session 3: 8.92E+10 ± 2.18E+10, session 4: 7.93E+10 ± 1.83E+10; $F_{1.05,7.348} = 5.18$, $p = 0.034$, $\eta_P^2 = 0.428$). According to the outcomes of the Helmert contrast tests, significant differences occurred between the first session and the others ($F_{1,7} = 5.14$, $p = 0.038$, $\eta_P^2 = 0.424$), and between the second session and the last two sessions ($F_{1,7} = 5.08$, $p = 0.041$, $\eta_P^2 = 0.413$). Mauchly's test indicated significant sphericity ($\chi2$ (5) = 64.94, $p = 0.01$) 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: 1314799 ± 575210, session 2: 414744 ± 244049, session 3: 72651 ± 19323, session 4: 62678 ± 18922; $F_{1.013,7.092} = 5.34$, $p = 0.027$, $\eta_P^2 = 0.436$). According to the Helmert contrast tests, significant differences emerged between the first session and the others ($F_{1,7} = 5.27$, $p = 0.032$, $\eta_P^2 = 0.428$), and between the second session and the last two sessions ($F_{1,7} = 5.18$, $p = 0.034$, $\eta_P^2 = 0.417$). 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.

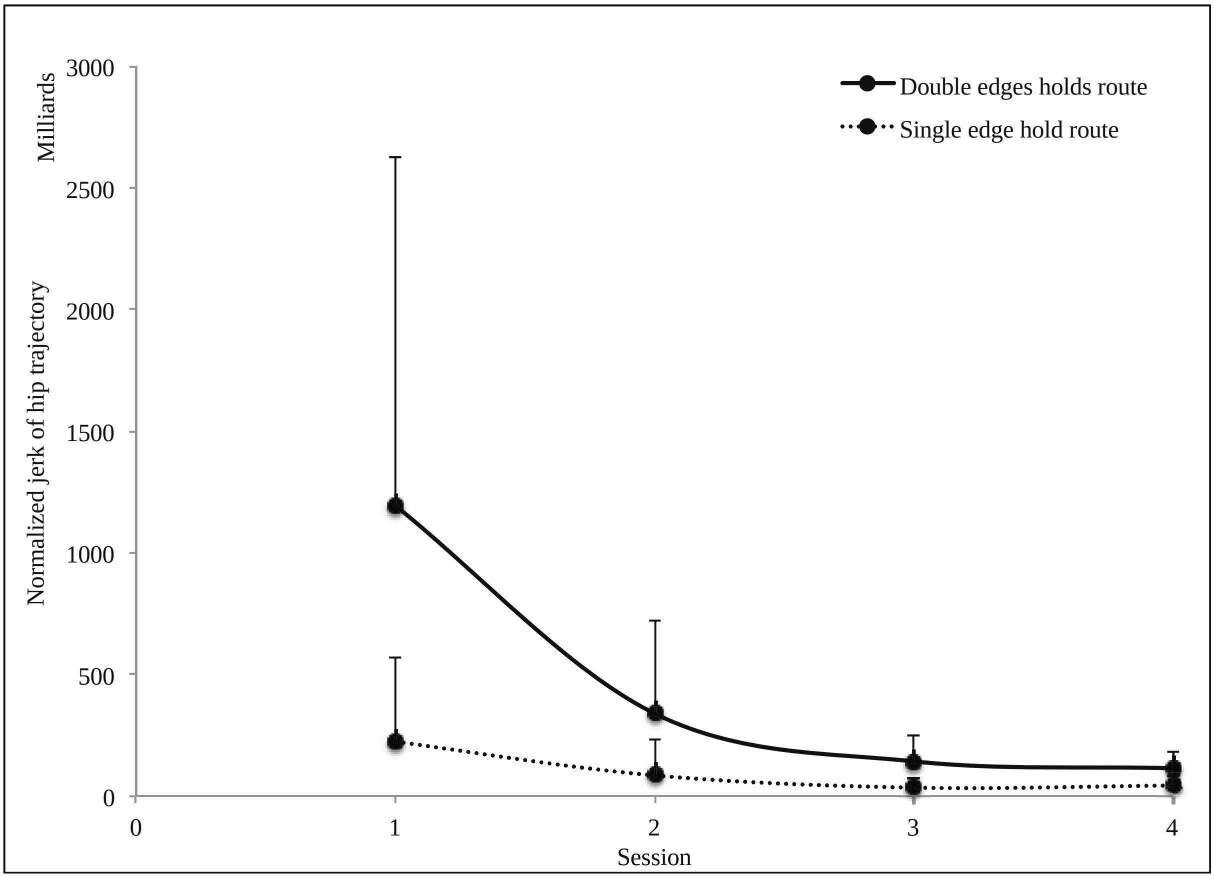

Figure 2. Differences of normalized jerk of hip trajectory between sessions for double edges holds route (black line) and horizontal edge holds route (dotted line).

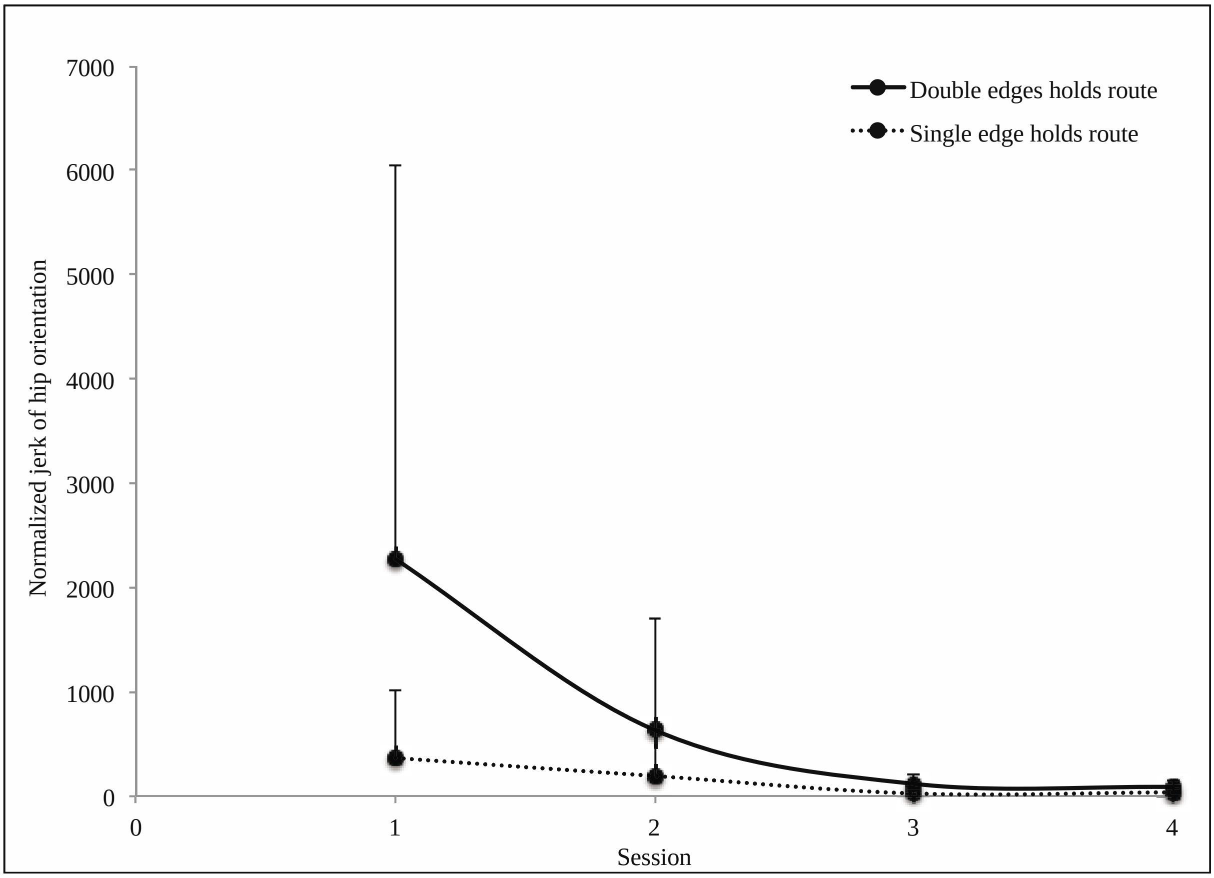

Figure 3. Differences of normalized jerk of hip orientation between sessions for double edges holds route (black line) and horizontal edge holds route (dotted line).

A significant positive correlation appears between the normalized jerk of hips trajectory smoothness and normalized jerk of hips orientation ($r = 0.83$, $p < 0.05$) (Figure 4). This finding signifies that the jerk of the trajectory can be measured via the jerk of its orientation or equivalently: both measures provide a similar measure of smoothness, the only difference being the scale of the two coefficients.

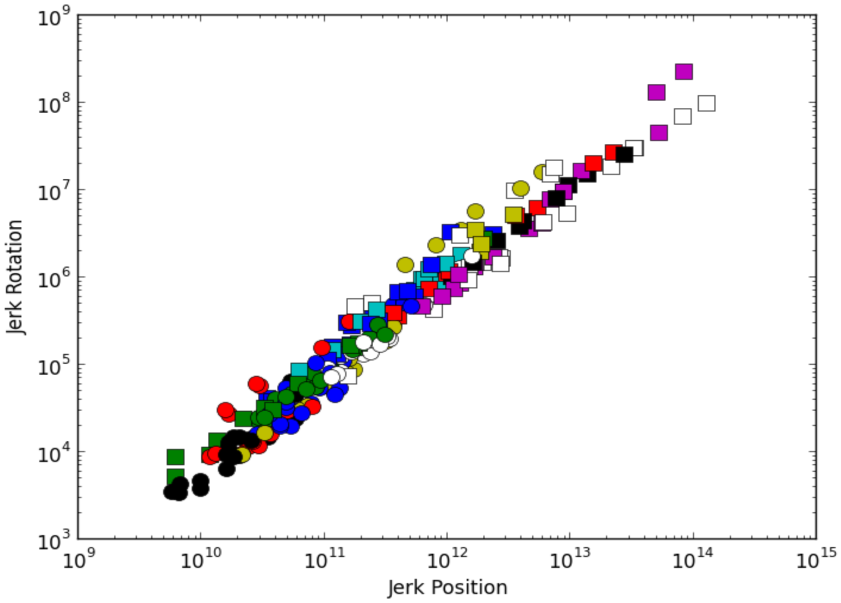

Figure 4. Correlation between jerk of hip trajectory (x-axis) and jerk of hip orientation (y-axis).

Last, our results showed improvement in climbing skills as climbers decreased the number of exploratory movements with practice in the simple and complex route designs (Table 1).

Table 1. Sum of number of exploratory movements for the six climbers on the simple and complex routes

	Session 1	Session 2	Session 3	Session 4
Simple route design	4	3	1	1
Complex route design	9	5	5	3

4. Discussion

High correlation values were observed between the normalized jerk values of hip trajectory and hip orientation revealing that both 3D translations and 3D oscillations of the hips can be used to assess climbing fluency. Our results showed that the normalized jerk values of hiptrajectory and orientation decreased with practice and were lower for the simple route design (i.e., horizontal edge holds grasping), confirming the usefulness of measuring jerk as an indicator of climbing fluency.

4.1. Relationships between climbing fluency and climbing wall design

Climbing the 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 a 'face-to-the-wall' body orientation, whereas vertical edge hold grasping induced a 'side-to-the-wall' body orientation (Seifert et al., 2013a). Therefore, the complex route design with holds offering dual edge orientations invited the climbers to explore two types of grasping patterns and body orientations (Seifert et al., 2013a) and involved higher jerk in both 3D translations and 3D oscillations of the hips. Indeed, moving between a right-orientated vertical edge hold to a left-orientated vertical edge hold would lead the body to oscillate like a door, a performance feature particularly well captured by recording the jerk of hip orientation. Previous studies have already shown how route design influences the kinematics of climbers, notably the value of movement time during hold grasping (Nougier et al., 1993) and the entropy measure of hip displacement(Sanchez et al., 2010). More precisely, complexity of manual grips (2 cm *vs.* 1 cm depth) and posture difficulty (low *vs.* high inclination of the foot holds) led to shorter movement time of grasping; in particular, longer times to reach the maximum acceleration and shorter times to reach the maximum deceleration were observed (Nougier et al., 1993). Moreover, complex hold grip and difficult posture emerged occasionally during the route that corresponded to a ‘crux’ (i.e., most difficult section of the route) or all over the route (Phillips et al., 2012). It was found that the crux led to a higher entropy value for hip displacement and higher movement time for skilled climbers than for less skilled climbers (Sanchez et al., 2010), supporting the utility of computing jerk as precisely as possible by taking into account both the hip trajectory and orientation.

4.2. Relationships between climbing fluency and practice

Our results showed a critical drop of jerk between the first and remaining three sessions, with stabilization emerging between the last two sessions. These results clarify contradictory data from previous studies that analysed the effect of practice on jerk minimization (Schneider and Zernicke, 1989; Young and Marteniuk, 1997). When arm movements were trained at different speeds, Schneider and Zernicke (Schneider and Zernicke, 1989) showed that jerk decreased for the slowest hand movement with practice. Conversely, when learning to kick, participants (Young and Marteniuk, 1997) revealed different jerk values for movements with similar trajectories, which did not support the jerk minimizing hypothesis with practice. In our study, high standard deviation values of jerk for hip trajectory and orientation (i.e., inter-individual variability) 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 (Cordier et al., 1993). Indeed, it is commonly accepted that performance could vary according to prior knowledge of routes (Phillips et al., 2012; Sanchez et al., 2012), which could explain the increase in climbing fluency observed between the first and second session in our study. 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 (Phillips et al., 2012). 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 (Sanchez et al., 2012). 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 climbing fluency. Improvement in route finding (i.e., interpretation of the ever-changing structure of the climbing wall design (Cordier et al., 1994)) could further explain the drop of jerk values and the decrease in the number of exploratory movements with practice. Indeed, Cordier et al. (1994, 1993) have already reported that practice can lead to a lower number and duration of stops, less exploration during route finding and lower entropy values of hip displacement, imputing greater climbing fluency. To summarise, the computation of jerk of hip trajectory and orientation in this study provided two complementary indicators of climbing fluency that seemed to provide a valuable contribution to understanding the effects of practice and route design on climbing performance.

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