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

3

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25

26 **Abstract**

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

37

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

40

41

42 **1. Introduction**

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

58 The sport of rock climbing involves both upper and lower-limbs for reaching and grasping
59 holds, and climbing up a rock surface with the feet. It is particularly valuable to assess the
60 validity of the minimizing jerk hypothesis as a potential indicator of fluency in climbing
61 performance. A previous study exploring self-handicap factors on successful climbing
62 performance highlighted that competitive climbers exhibited performance anxiety through
63 rigid posture and jerky movements which could limit performance by reducing movement
64 fluency (Ferrand et al., 2006). Rock climbing involves interspersed periods of maintaining
65 body equilibrium on a more or less vertical climbing surface (Bourdin et al., 1999, 1998;

66 Testa et al., 2003, 1999), with combining upper and lower limb movements to ascend these
67 surfaces rapidly (Boschker et al., 2002; Nougier et al., 1993; Sibella et al., 2007). During
68 performance, the alternation of periods dedicated to postural regulation and to quadruped
69 displacement on a vertical surface, might lead to a drop in measures of climbing fluency that
70 is fundamental to quantify. Previous studies have assessed the fluency of climbing
71 movements by: (i) implementing a harmonic analysis of the acceleration of the hips (Cordier
72 et al., 1996), by quantifying the duration of a static position as any point throughout the climb
73 where the hips were not in motion (Billat et al., 1995; Sanchez et al., 2012; Seifert et al.,
74 2013b); and (ii), by measuring the geometric entropy index value from the displacement of
75 the hips (Boschker and Bakker, 2002; Cordier et al., 1994, 1993; Sanchez et al., 2010; Sibella
76 et al., 2007). Harmonic analysis is a tool for observing the structure of the dynamics of a
77 movement. Using Fourier transformation, Cordier and colleagues (Cordier et al.,
78 1996) conducted a harmonic analysis revealing that the expert climbing performance could be
79 characterized by a pendulum oscillating as a mass-spring system that works like a dissipative
80 system, i.e., a system where dissipation of energy is minimized by harmonic movements.
81 Although very promising, the study of Cordier et al. (1996) only considered the displacement
82 of the hips in 2D (i.e., movement projection in the vertical plane), whereas recent studies have
83 highlighted the prevalence of antero-posterior and lateral sway during climbing performance
84 (Sibella et al., 2007; Zampagni et al., 2011), supporting the importance of 3D movement
85 analysis. Similar limitations emerge from the use of the geometric entropy index, (Boschker
86 and Bakker, 2002; Cordier et al., 1994, 1993; Sanchez et al., 2010; Sibella et al., 2007). The
87 geometric index of entropy (H) was calculated by recording the distance covered by the body
88 (L) and the convex hull (c) according to the following equation: $H = \log_2 2L/c$ (Cordier et al.,
89 1994, 1993). According to Cordier et al. (Cordier et al., 1994, 1993), geometric entropy
90 measures reveal the amount of fluency/curvature of a curve: the higher the entropy, the higher

91 the disorder of the system; therefore, a low entropy value was associated with a low energy
92 expenditure and greater climbing fluency. Regardless, geometric entropy index remains a
93 spatial analysis of the body motion that does not consider the displacement of the hips over
94 time. This is an omission since both hip translations and oscillations in 3D should be
95 considered to assess climbing fluency. The aim of this study was to explore whether the
96 computation of jerk coefficient values could provide an indicator of climbing fluency,
97 achieved by computing the jerk of hip trajectory and hip orientation and examining their
98 correlation. We also sought to investigate whether jerk is minimized with practice and
99 modifications to climbing wall design (simple *vs.* complex hold grasping patterns).

100 **2. Methods**

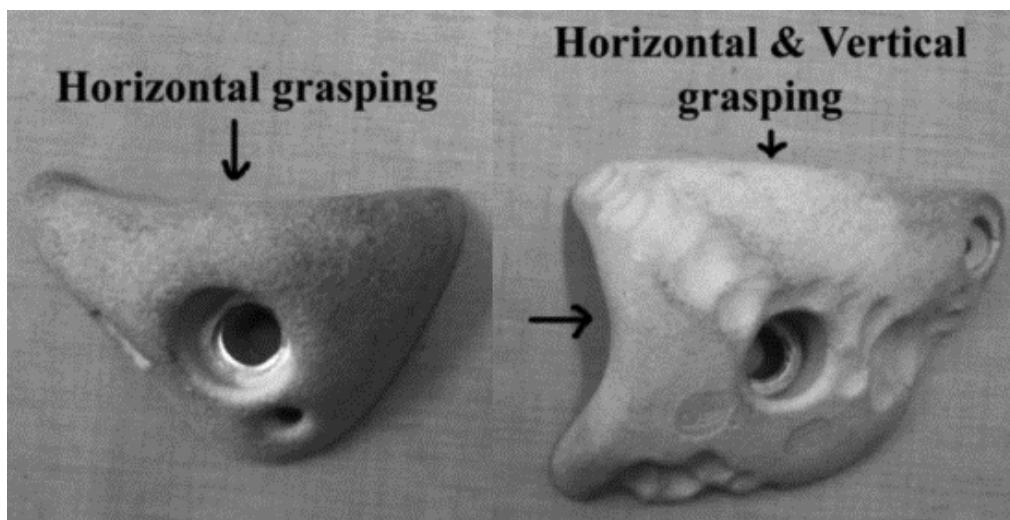
101 *2.1. Participants*

102 Eight students of a Faculty of Sport Sciences voluntary participated to this study (mean age:
103 21.4 ± 2.4 yr; mean height: 170.1 ± 9.5 cm; mean weight: 69.9 ± 5.5 kg). These climbers had
104 climbing experience of 4.1 ± 2.1 yr, trained for 3.4 ± 1.9 hours per week and had a rock
105 climbing ability of 6a on the French Rating Scale of Difficulty (F-RSD) (Delignières et al.,
106 1993), which corresponds to an intermediate level of performance (Draper et al., 2011).
107 Climbing ability was defined as the most difficult ascent by top rope (Delignières et al.,
108 1993).

109 *2.2. Protocol*

110 Each climber participated in four testing sessions (separated by two days of rest), each
111 consisting of two different route ascents. Participants were randomly allocated to climb two
112 routes of a similar grade rated 5c on the F-RSD. Each route was identifiable by colour and
113 was set on an artificial indoor climbing wall by two certified route setters who ensured that
114 they matched intermediate climbing levels). The routes had the same height (10 m) and were
115 composed of 20 hand holds each, located at the same place on the artificial wall. Only the

116 orientation of the hold was changed between the two routes: the first route was designed to
117 allow horizontal edge hold grasping, while the second route was designed to allow both
118 horizontal and vertical edges hold grasping (Fig. 1). This design allowed us to examine
119 whether the level of grasping uncertainty could constrain climbing fluency. Participants were
120 instructed to self-pace their ascent, to climb fluently and to climb without falling. Each route
121 was top-roped, i.e., routes were climbed with the rope anchored above the climber at all times.
122 Each ascent was preceded by 3 minutes of route preview, as pre-ascent visual inspection is a
123 key climbing performance parameter (Sanchez et al., 2012). The protocol was approved by
124 the local University ethics committee and followed the declaration of Helsinki. Procedures
125 were explained to the climbers, who then gave their written informed consent to participate.



126
127 Figure 1. Orientation and shape of the holds for the two routes. The arrow indicates the
128 preferential edge grasping allowed by the hold.

129
130 *2.3. Data collection*

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

135 purpose (Minami et al., 2011, 2010). In our study, an IMU corresponded to a combination of
136 a tri-axial accelerometer ($\pm 8G$), tri-axial gyroscope ($1600^\circ.s^{-1}$) and a tri-axial magnetometer
137 (*MotionPod*, Movea©, Grenoble, France). Data collected from the IMU (with
138 *MotionDevTool*, Movea©, Grenoble, France) were recorded with North magnetic reference
139 and at a 100 Hz sample frequency.

140 2.4. Data collection and analysis methods

141 The first step towards computation of jerk coefficients was to compute hip orientation in
142 Earth reference frame and follow its orientation changes. Raw accelerometer readings cannot
143 be used directly to compute the jerk coefficient due to orientation changes during ascent. The
144 solution to this problem was found by tracking sensor orientation by using the complementary
145 filter based algorithm (Madgwick, 2010; Madgwick et al., 2011), which integrated the three
146 sensor information sources (i.e., accelerometer, gyroscope and magnetometer). The gyroscope
147 measured precise angular changes at very short time durations but could not be used to track
148 the angle changes by integration due to the problem of drift. The accelerometer provided
149 absolute, albeit noisy, measurements of hip acceleration and the Earth's gravitational force at
150 the same time. By combining the two sensor information sources it was possible to reduce
151 drift of the gyroscope for hip orientation tracking. When magnetometer information was
152 added, it was possible to compute orientation of the sensor with respect to the fixed frame of
153 Earth reference (magnetic north, East and gravity directions) (Madgwick, 2010; Madgwick et
154 al., 2011).

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

159 the acceleration of hip at time t in the fixed Earth reference frame can be expressed as

$$160 \quad a_t^{GF} = R_t a_t^{SF}.$$

161 The third step consisted of assessing smoothness of the hip trajectory by computing the jerk
162 coefficient from processed 3D accelerometer signals a_t^{GF} . Jerk is a measure of the lack of
163 smoothness of a joint or limb segment during performance. For a smooth trajectory $x^{GF} \in \mathcal{C}^3$,

$$164 \quad \text{the jerk } J_{x^{GF}}(t) \text{ was defined as: } J_{x^{GF}}(T) = C \int_0^T \left\| \ddot{x}_s^{GF} \right\|^2 ds$$

165 where C was a normalization constant to make the quantity dimensionless (Hogan and
166 Sternad, 2009). In practice instead of computing x_t^{GF} (position on the wall) from a_t^{GF} with
167 successive integration, the term \ddot{x}_s^{GF} was replaced by \dot{a}_t^{GF} . By derivation of a_t^{GF} , the constant
168 gravity acceleration was removed, leaving only the hip acceleration component.

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

172 chosen such that $C = \frac{T^5}{(\Delta x^{GF})^2}$, where Δx^{GF} was the climbing height and T the time needed to

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

179 A second indicator of climbing fluency consisted of computing jerk coefficient measuring hip
180 orientation smoothness. Indeed, as stated previously, hip displacements of climbers not only
181 correspond to 3D translations, but also to 3D orientation oscillations (Cordier et al., 1996;
182 Sibella et al., 2007; Zampagni et al., 2011). These results highlighted the interest of studying

183 jerk now defined from hip orientation $R_t \in SO(3)$. In this case the previous equation could
184 not be used directly and some technical adjustments were required. Due to the structure of
185 $SO(3)$, orientation acceleration could not be obtained by directly considering successive
186 derivation of R_t as a 3x3 matrix. The solution to this problem in our study consisted of
187 constructing a process $z_t \in \mathbb{R}^3$ such that its velocity was the angular velocity of R_t , which
188 can be differentiated easily (note that z_t and R_t are of the same dimensionality). We define
189 z_t as $\dot{z}_t = \dot{R}_t R_t^{-1}$
190 where $R_t^{-1} = R_t^T$ which is due to orthogonality of the elements of $SO(3)$. If R_t has an angular
191 velocity ω_t , then $\dot{z}_t = \omega_t$. Therefore, working on z_t allowed us to eliminate all the non-linear
192 issues inherent to $SO(3)$ and work in \mathbb{R}^3 instead, where derivative was carried out simpler
193 than in $SO(3)$. In practice, due to the discretization of observations of R_t with a sampling
194 time δt , the process z_t was approximated by $\widetilde{z}_k \approx z_{k\delta t}$, with \widetilde{z} recursively computed as
195 $\widetilde{z}_{k+1} - \widetilde{z}_k = \log(R_{(k+1)\delta t} R_{k\delta t}^{-1})$ where \log was the inverse application of the matrix
196 exponential. In our study, jerk of orientation was defined as $J_z(T)$.

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

206 2.5. Statistical analysis

207 After the computation of the jerk from z_t for each session, differences of jerk coefficients

208 between sessions and route designs were compared by two-way repeated measures ANOVA
209 (practice across four sessions (4) and climbing wall design across two different routes (2))
210 using SPSS Statistics 20.0. Sphericity was verified by the Mauchly test (Winter et al., 2001).
211 When the assumption of sphericity was not met, the significance of F -ratios was adjusted
212 according to the Greenhouse-Geisser procedure. Then, Helmert contrast tests enabled us to
213 compare each session with the performance mean of the other sessions, in order to determine
214 whether jerk reduced with practice and whether route design influenced jerk values. Here it
215 was predicted that routes providing double edges (vertical and horizontal) grasping patterns
216 would be associated with more jerk compared to the route where only horizontal grasping was
217 afforded. Partial eta squared (η_p^2) statistics were calculated as an indicator of effect size,
218 considering that $\eta_p^2 = 0.01$ represents a small effect, $\eta_p^2 = 0.06$ represents a medium effect
219 and $\eta_p^2 = 0.15$ represents a large effect (Cohen, 1988). Pearson correlation tests were also
220 performed to examine the relationships between jerk of hip trajectory $J_x(T)$ and jerk of hip
221 orientation $J_z(T)$. For all tests, the level of significance was fixed at $p < 0.05$.

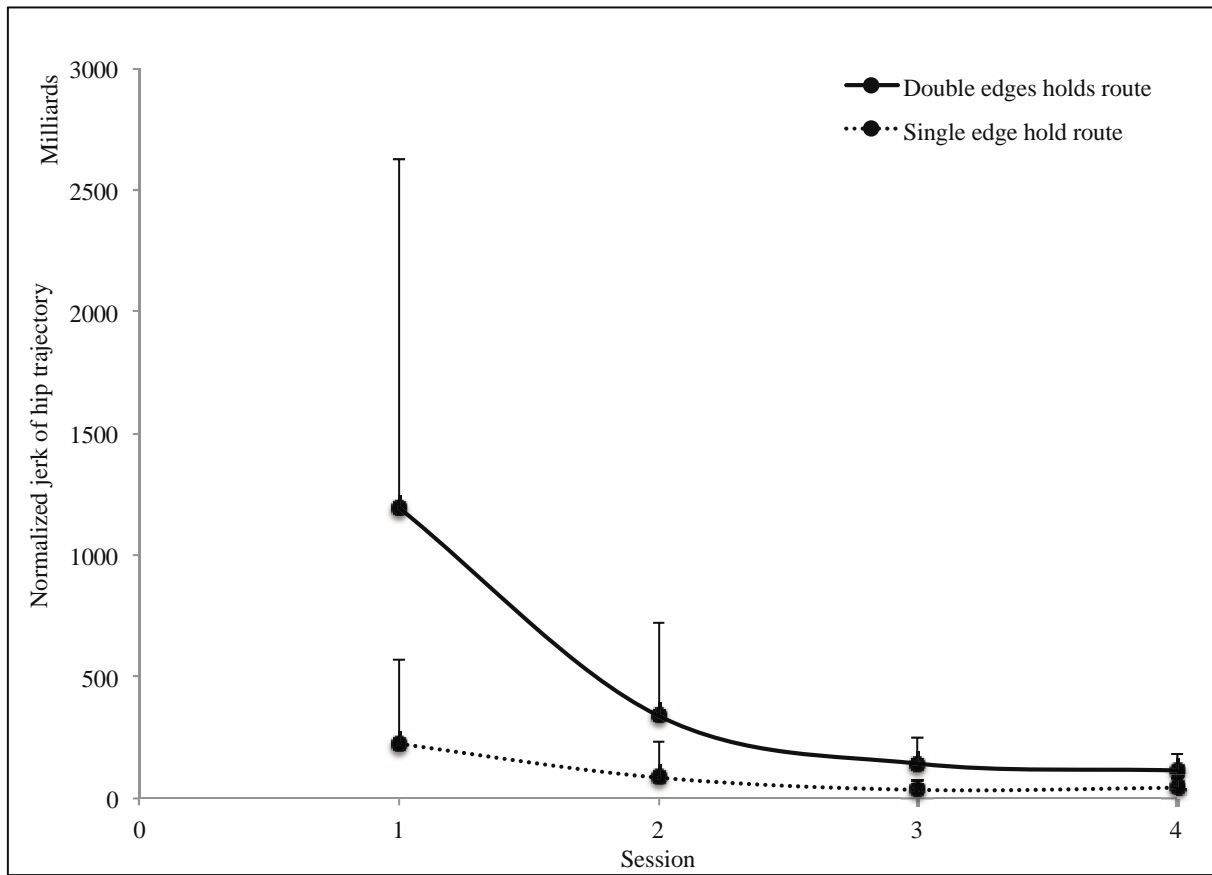
222

223 3. Results

224 Significantly higher values of normalized jerk for hip trajectory emerged in the double edges
225 holds route in comparison to the horizontal edge holds route ($4.48E+11 \pm 1.77E+11$ vs.
226 $9.65E+10 \pm 4.44E+10$; $F_{1,7} = 6.14$, $p = 0.03$, $\eta_p^2 = 0.463$). Similar results were observed for
227 normalized jerk of hip orientation; this latter measure was higher for the double edges holds
228 route in comparison to horizontal edge holds route (776846 ± 434836 vs. 155590 ± 96743 ;
229 $F_{1,7} = 6.22$, $p = 0.028$, $\eta_p^2 = 0.442$).

230 To examine session effect, Mauchly's test indicated significant sphericity ($\chi^2(5) = 38.55$, $p =$
231 0.01), so the Greenhouse-Geisser correction was applied and showed significant differences
232 of normalized jerk of hip trajectory between sessions (session 1: $\pm 2.93E+11$, session 2:

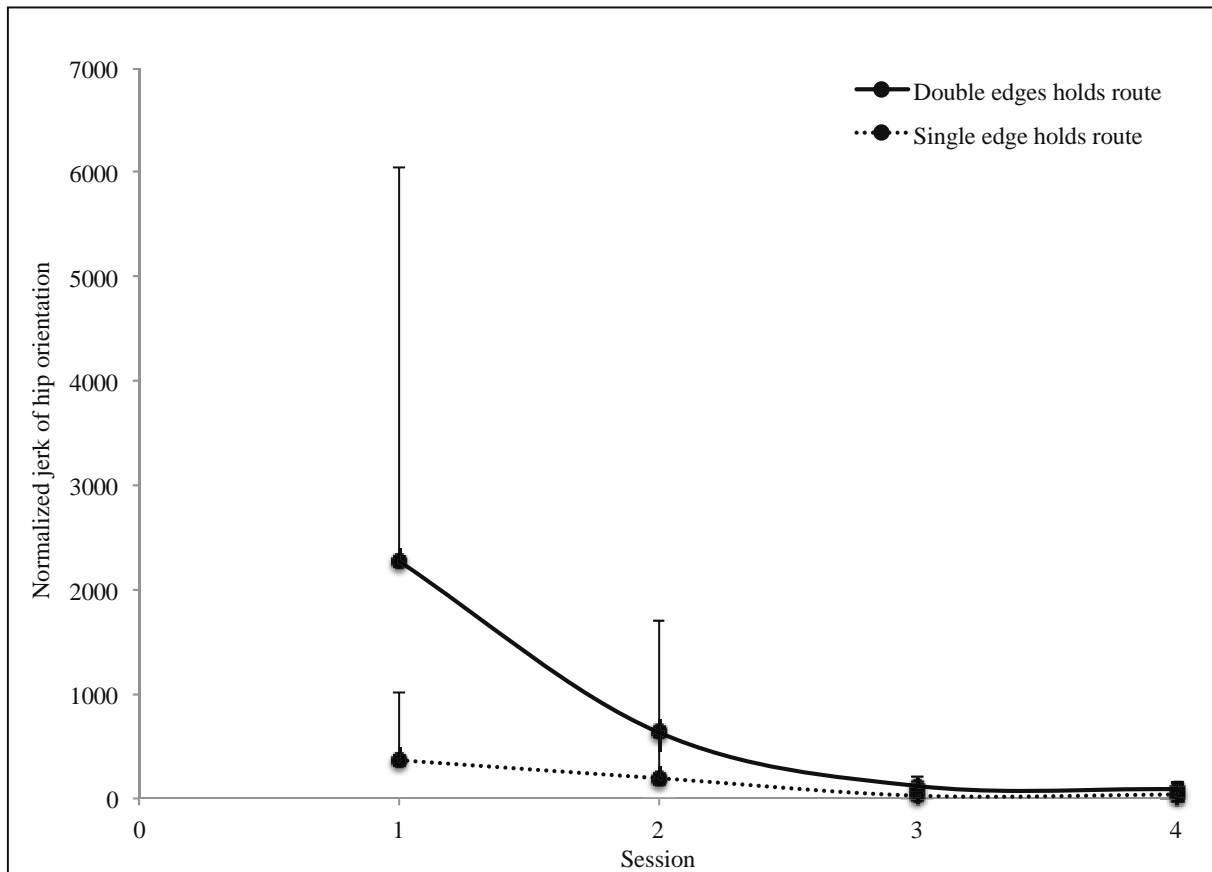
233 $2.13\text{E}+11 \pm 9.11\text{E}+10$, session 3: $8.92\text{E}+10 \pm 2.18\text{E}+10$, session 4: $7.93\text{E}+10 \pm 1.83\text{E}+10$;
234 $F_{1,05,7,348} = 5.18$, $p = 0.034$, $\eta_p^2 = 0.428$). According to the outcomes of the Helmert contrast
235 tests, significant differences occurred between the first session and the others ($F_{1,7} = 5.14$, $p =$
236 0.038 , $\eta_p^2 = 0.424$), and between the second session and the last two sessions ($F_{1,7} = 5.08$, $p =$
237 0.041 , $\eta_p^2 = 0.413$). Mauchly's test indicated significant sphericity ($\chi^2(5) = 64.94$, $p = 0.01$)
238 when differences of normalized jerk of hip orientation were analysed between sessions. Thus,
239 the Greenhouse-Geisser correction was applied, revealing significant differences between
240 sessions (session 1: 1314799 ± 575210 , session 2: 414744 ± 244049 , session 3: $72651 \pm$
241 19323 , session 4: 62678 ± 18922 ; $F_{1,013,7,092} = 5.34$, $p = 0.027$, $\eta_p^2 = 0.436$). According to the
242 Helmert contrast tests, significant differences emerged between the first session and the others
243 ($F_{1,7} = 5.27$, $p = 0.032$, $\eta_p^2 = 0.428$), and between the second session and the last two sessions
244 ($F_{1,7} = 5.18$, $p = 0.034$, $\eta_p^2 = 0.417$). Figure 2 illustrates the differences of normalized jerk of
245 hip trajectory between sessions for the two routes and Figure 3 illustrates the differences of
246 normalized jerk of hip orientation between sessions for the two routes.



247

248 Figure 2. Differences of normalized jerk of hip trajectory between sessions for double edges

249 holds route (black line) and horizontal edge holds route (dotted line).

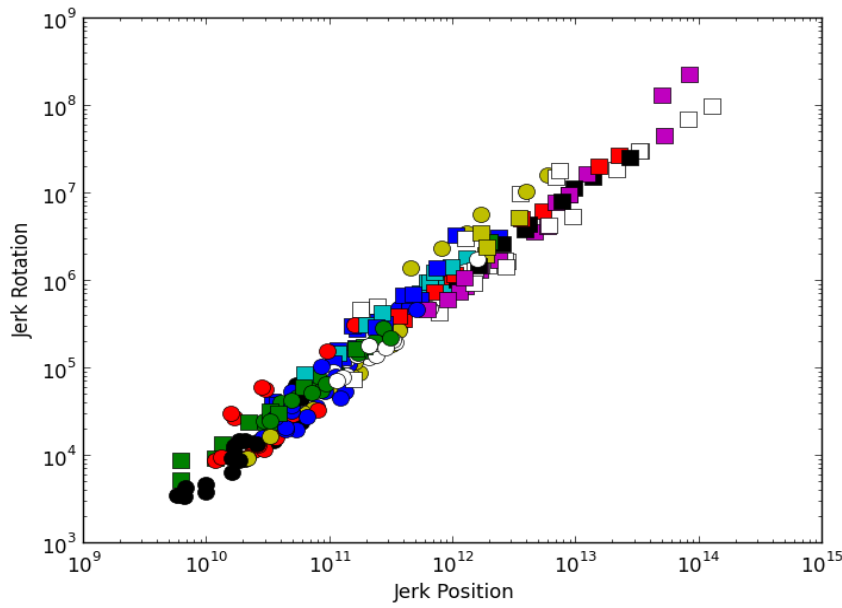


250

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

253

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



259

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

262

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

265

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

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

268

269

270 **4. Discussion**

271 High correlation values were observed between the normalized jerk values of hip trajectory
 272 and hip orientation revealing that both 3D translations and 3D oscillations of the hips can be

273 used to assess climbing fluency. Our results showed that the normalized jerk values of
274 hip trajectory and orientation decreased with practice and were lower for the simple route
275 design (i.e., horizontal edge holds grasping), confirming the usefulness of measuring jerk as
276 an indicator of climbing fluency.

277 *4.1. Relationships between climbing fluency and climbing wall design*

278 Climbing the route with horizontal edge holds resembled the action of grasping the rungs of a
279 ladder, explaining how lower normalized jerk values of both hip trajectory and orientation
280 emerged in the simple route than rather the complex route. Horizontal edge hold grasping led
281 to a 'face-to-the-wall' body orientation, whereas vertical edge hold grasping induced a 'side-
282 to-the-wall' body orientation (Seifert et al., 2013a). Therefore, the complex route design with
283 holds offering dual edge orientations invited the climbers to explore two types of grasping
284 patterns and body orientations (Seifert et al., 2013a) and involved higher jerk in both 3D
285 translations and 3D oscillations of the hips. Indeed, moving between a right-orientated
286 vertical edge hold to a left-orientated vertical edge hold would lead the body to oscillate like a
287 door, a performance feature particularly well captured by recording the jerk of hip orientation.
288 Previous studies have already shown how route design influences the kinematics of climbers,
289 notably the value of movement time during hold grasping (Nougier et al., 1993) and the
290 entropy measure of hip displacement (Sanchez et al., 2010). More precisely, complexity of
291 manual grips (2 cm vs. 1 cm depth) and posture difficulty (low vs. high inclination of the foot
292 holds) led to shorter movement time of grasping; in particular, longer times to reach the
293 maximum acceleration and shorter times to reach the maximum deceleration were observed
294 (Nougier et al., 1993). Moreover, complex hold grip and difficult posture emerged
295 occasionally during the route that corresponded to a 'crux' (i.e., most difficult section of the
296 route) or all over the route (Phillips et al., 2012). It was found that the crux led to a higher
297 entropy value for hip displacement and higher movement time for skilled climbers than for

298 less skilled climbers (Sanchez et al., 2010), supporting the utility of computing jerk as
299 precisely as possible by taking into account both the hip trajectory and orientation.

300 4.2. *Relationships between climbing fluency and practice*

301 Our results showed a critical drop of jerk between the first and remaining three sessions, with
302 stabilization emerging between the last two sessions. These results clarify contradictory data
303 from previous studies that analysed the effect of practice on jerk minimization (Schneider and
304 Zernicke, 1989; Young and Marteniuk, 1997). When arm movements were trained at different
305 speeds, Schneider and Zernicke (Schneider and Zernicke, 1989) showed that jerk decreased
306 for the slowest hand movement with practice. Conversely, when learning to kick, participants
307 (Young and Marteniuk, 1997) revealed different jerk values for movements with similar
308 trajectories, which did not support the jerk minimizing hypothesis with practice. In our study,
309 high standard deviation values of jerk for hip trajectory and orientation (i.e., inter-individual
310 variability) emerged in the first practice session, which could have been due to absence of
311 prior knowledge of route finding that may have led to a search process in participants
312 (Cordier et al., 1993). Indeed, it is commonly accepted that performance could vary
313 according to prior knowledge of routes (Phillips et al., 2012; Sanchez et al., 2012), which
314 could explain the increase in climbing fluency observed between the first and second session
315 in our study. In fact, three different conditions of practice may influence climbing fluency:
316 on-sight climbing involves successful climbing with no prior knowledge of the climb; flash
317 climbing means successful climbing at the first attempt after receiving prior knowledge of the
318 climb; red-point climbing signifies successful climbing without falling after previous
319 unsuccessful attempts (Phillips et al., 2012). These assumptions have been confirmed by a
320 recent study that showed significant reductions in the number and duration of stops when
321 climbing with a route preview (Sanchez et al., 2012). To consider the possible effects of
322 previewing on climbing fluency, three minutes of previewing were allowed in our study.

323 However, route previewing does not appear to be the main constraint on climbing fluency.
324 Improvement in route finding (i.e., interpretation of the ever-changing structure of the
325 climbing wall design (Cordier et al., 1994)) could further explain the drop of jerk values and
326 the decrease in the number of exploratory movements with practice. Indeed, Cordier et al.
327 (1994, 1993) have already reported that practice can lead to a lower number and duration of
328 stops, less exploration during route finding and lower entropy values of hip displacement,
329 imputing greater climbing fluency. To summarise, the computation of jerk of hip trajectory
330 and orientation in this study provided two complementary indicators of climbing fluency that
331 seemed to provide a valuable contribution to understanding the effects of practice and route
332 design on climbing performance.

333

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