



**HAL**  
open science

# Climbing Skill and Complexity of Climbing Wall Design: Assessment of Jerk as a Novel Indicator of Performance Fluency

Ludovic Seifert, Dominic Orth, Jérémie Boulanger, Vladislavs Dovgalecs,  
Romain Hérault, Keith Davids

## ► To cite this version:

Ludovic Seifert, Dominic Orth, Jérémie Boulanger, Vladislavs Dovgalecs, Romain Hérault, et al.. Climbing Skill and Complexity of Climbing Wall Design: Assessment of Jerk as a Novel Indicator of Performance Fluency. *Journal of Applied Biomechanics*, 2014, 30 (5), pp.619-625. 10.1123/jab.2014-0052 . hal-02094928

**HAL Id: hal-02094928**

**<https://hal.science/hal-02094928>**

Submitted on 17 Feb 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Climbing skill and complexity of climbing wall design : assessment of jerk as a novel indicator of performance fluency

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

Available from Sheffield Hallam University Research Archive (SHURA) at:

<http://shura.shu.ac.uk/8793/>

---

This document is the author deposited version. You are advised to consult the publisher's version if you wish to cite from it.

### Published version

SEIFERT, Ludovic, ORTH, Dominic, BOULANGER, Jérémie, DOVGALECS, Vladislavs, HÉRAULT, Romain and DAVIDS, Keith (2014). Climbing skill and complexity of climbing wall design : assessment of jerk as a novel indicator of performance fluency. *Journal of applied biomechanics*, 30 (5), 619-625.

---

### Copyright and re-use policy

See <http://shura.shu.ac.uk/information.html>

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

3

4 Ludovic Seifert<sup>1\*</sup>, Dominic Orth<sup>1,2</sup>, Jérémie Boulanger<sup>1</sup>, Vladislavs Dovgalecs<sup>1</sup>, Romain  
5 Hérault<sup>3</sup>, Keith Davids<sup>4,5</sup>

6

7 <sup>1</sup> CETAPS - EA 3832, Faculty of Sport Sciences, University of Rouen, France

8 <sup>2</sup> School of Human Movement Studies, Queensland University of Technology, Brisbane,  
9 Australia

10 <sup>3</sup> LITIS - EA 4108, National Institute of Applied Sciences (INSA), Rouen, France

11 <sup>4</sup> Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, , United  
12 Kingdom

13 <sup>5</sup> FiDiPro Programme, University of Jyväskylä, Finland

14

15 \* corresponding author :

16 Ludovic Seifert

17 CETAPS - EA 3832

18 Faculty of Sport Sciences

19 University of Rouen

20 Boulevard Siegfried

21 76821 Mont Saint Aignan cedex

22 France

23

24

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**

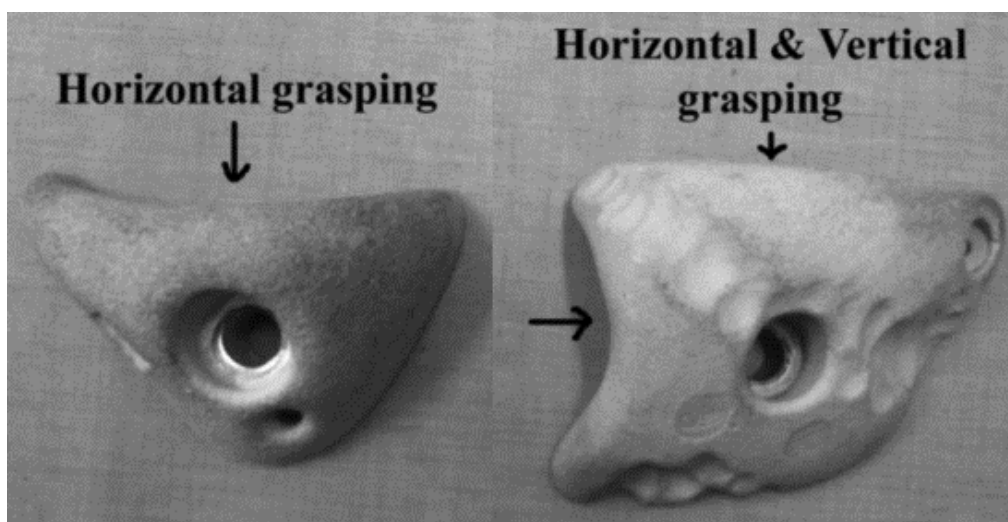
### 101 *2.1. Participants*

102 Eight students of a Faculty of Sport Sciences voluntary participated to this study (mean age:  
103  $21.4 \pm 2.4$  yr; mean height:  $170.1 \pm 9.5$  cm; mean weight:  $69.9 \pm 5.5$  kg). These climbers had  
104 climbing experience of  $4.1 \pm 2.1$  yr, trained for  $3.4 \pm 1.9$  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  $\Delta x^{GF}$  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  $\omega_t$ , 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  $\delta t$ , 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 ( $\eta_p^2$ ) 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  $p < 0.05$ .

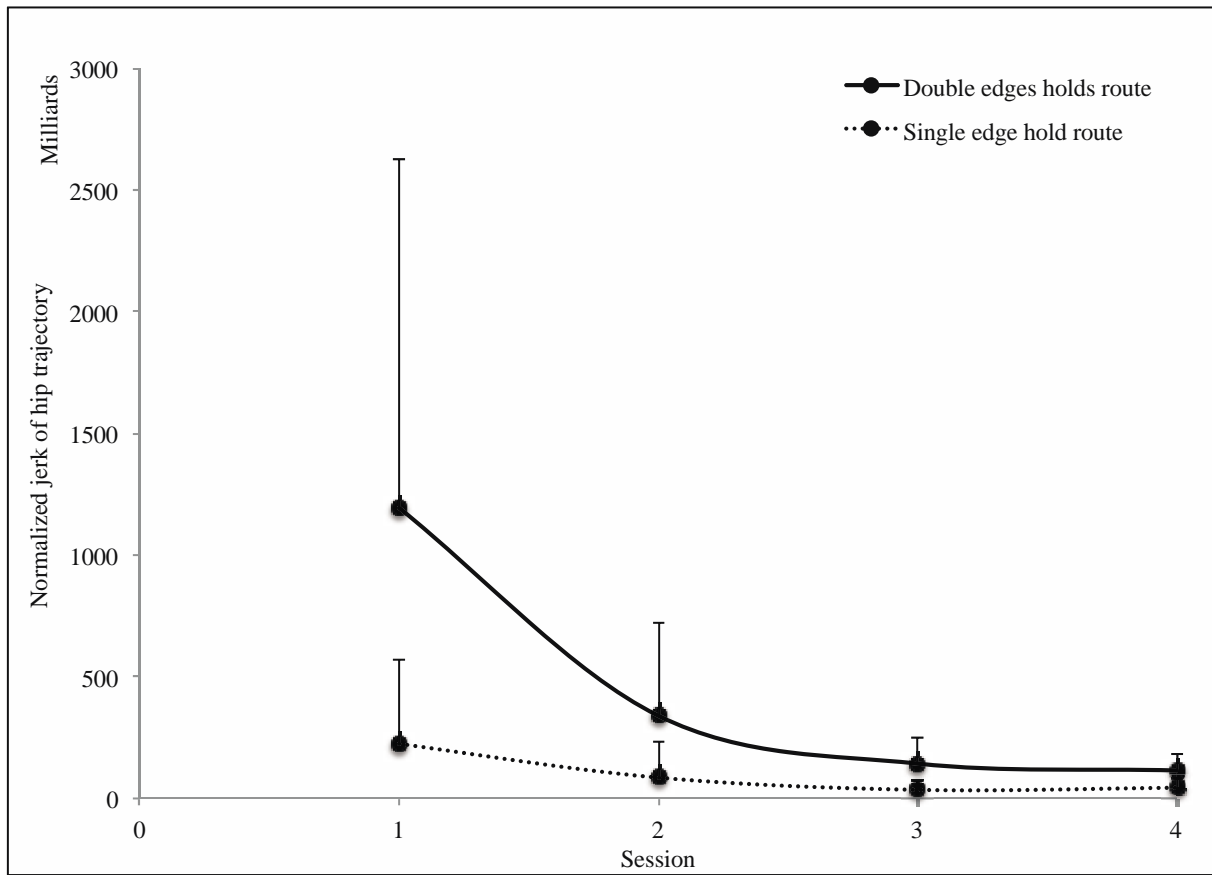
222

### 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 ( $776846 \pm 434836$  vs.  $155590 \pm 96743$ ;  
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:

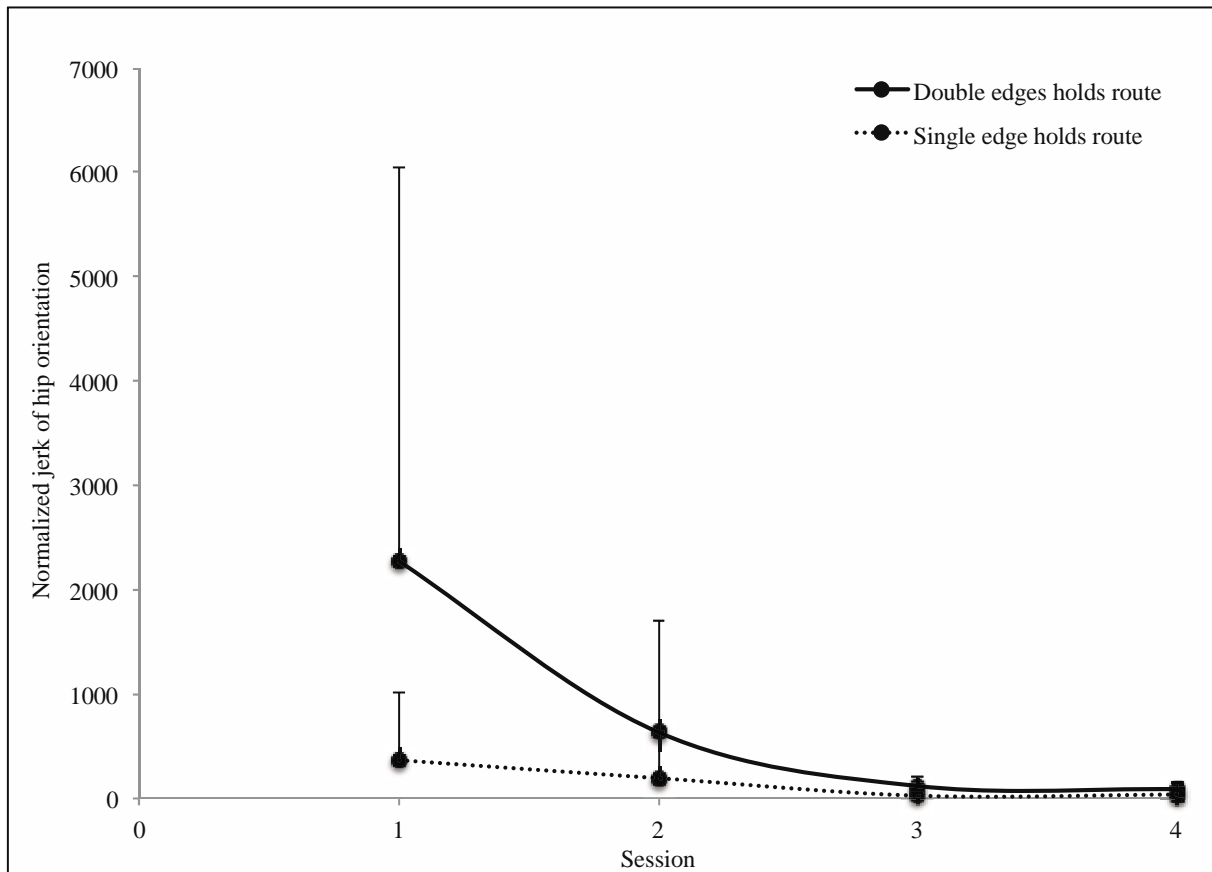
233  $2.13\text{E}+11 \pm 9.11\text{E}+10$ , session 3:  $8.92\text{E}+10 \pm 2.18\text{E}+10$ , session 4:  $7.93\text{E}+10 \pm 1.83\text{E}+10$ ;  
234  $F_{1,05,7,348} = 5.18$ ,  $p = 0.034$ ,  $\eta_p^2 = 0.428$ ). According to the outcomes of the Helmert contrast  
235 tests, significant differences 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:  $1314799 \pm 575210$ , session 2:  $414744 \pm 244049$ , session 3:  $72651 \pm$   
241  $19323$ , session 4:  $62678 \pm 18922$ ;  $F_{1,013,7,092} = 5.34$ ,  $p = 0.027$ ,  $\eta_p^2 = 0.436$ ). 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).

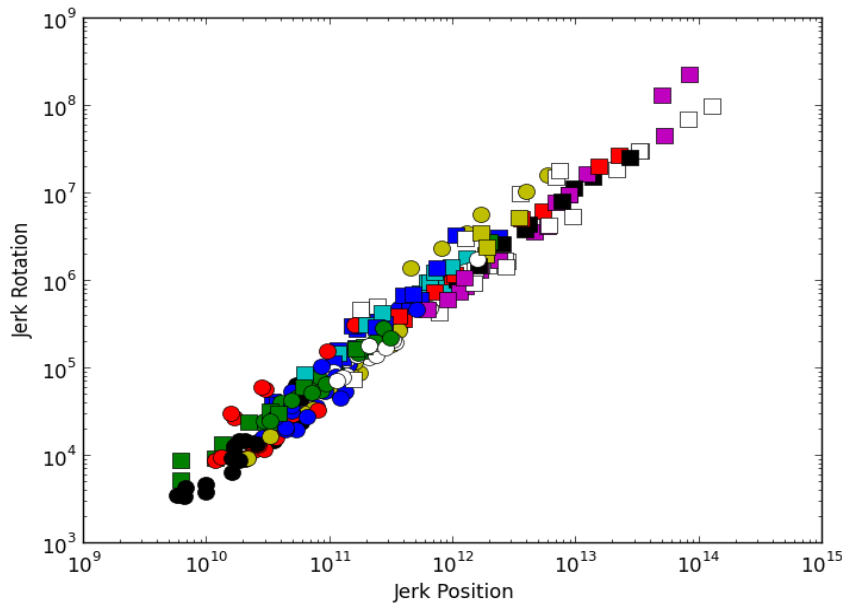


250

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

#### 334 **References**

- 335 Billat, V., Palleja, P., Charlaix, T., Rizzardo, P., Janel, N., 1995. Energy specificity of rock  
336 climbing and aerobic capacity in competitive sport rock climbers. *J. Sports Med. Phys.*  
337 *Fitness* 35, 20–4.
- 338 Boschker, M.S.J., Bakker, F., Michaels, C.F., 2002. Memory for the functional characteristics  
339 of climbing walls: perceiving affordances. *J. Mot. Behav.* 34, 25–36.
- 340 Boschker, M.S.J., Bakker, F.C., 2002. Inexperienced sport climbers might perceive and utilize  
341 new opportunities for action by merely observing a model. *Percept. Mot. Skills* 95, 3–9.
- 342 Bourdin, C., Teasdale, N., Nougier, V., 1998. High postural constraints affect the organization  
343 of reaching and grasping movements. *Exp. Brain Res.* 122, 253–9.
- 344 Bourdin, C., Teasdale, N., Nougier, V., Bard, C., Fleury, M., 1999. Postural constraints  
345 modify the organization of grasping movements. *Hum. Mov. Sci.* 18, 87–102.
- 346 Cohen, D., 1988. *Statistical power analysis for the behavioral science* (2nd Edition). Erlbaum,  
347 Hillsdale, NJ.
- 348 Cordier, P., Dietrich, G., Pailhous, J., 1996. Harmonic analysis of a complex motor behaviour.  
349 *Hum. Mov. Sci.* 15, 789–807.
- 350 Cordier, P., Mendès-France, M., Bolon, P., Pailhous, J., 1993. Entropy, degrees of freedom,  
351 and free climbing: a thermodynamic study of a complex behavior based on trajectory  
352 analysis. *Int. J. Sport Psychol.* 24, 370–378.

- 353 Cordier, P., Mendès-France, M., Pailhous, J., Bolon, P., 1994. Entropy as a global variable of  
354 the learning process. *Hum. Mov. Sci.* 13, 745–763.
- 355 Cuesta-Vargas, A.I., Galán-Mercant, A., Williams, J.M., 2010. The use of inertial sensors  
356 system for human motion analysis. *Phys. Ther. Rev.* 15, 462–473.
- 357 Delignières, D., Famose, J., Thépeaut-Mathieu, C., Fleurance, P., 1993. A psychophysical  
358 study of difficulty rating in rock climbing. *Int. J. Sport Psychol.* 24, 404–416.
- 359 Draper, N., Dickson, T., Blackwell, G., Fryer, S., Priestley, S., Winter, D., Ellis, G., 2011.  
360 Self-reported ability assessment in rock climbing. *J. Sports Sci.* 29, 851–8.
- 361 Ferrand, C., Tetard, S., Fontayne, P., 2006. Self-Handicapping in Rock Climbing: A  
362 Qualitative Approach. *J. Appl. Sport Psychol.* 18, 271–280.
- 363 Flash, T., Hogan, N., 1985. The coordination of arm movements: an experimentally  
364 confirmed mathematical model. *J. Neurosci.* 5, 1688–1703.
- 365 Goldvasser, D., McGibbon, C.A., Krebs, D.E., 2001. High curvature and jerk analyses of arm  
366 ataxia. *Biol. Cybern.* 84, 85–90.
- 367 Hogan, N., 1984. An organizing principle for a class of voluntary movements. *J. Neurosci.* 4,  
368 2745–2754.
- 369 Hogan, N., Sternad, D., 2009. Sensitivity of smoothness measures to movement duration,  
370 amplitude, and arrests. *J. Mot. Behav.* 41, 529–34.
- 371 Klein Breteler, M.D., Meulenbroek, R.G.J., Gielen, S.C.A.M., 2002. An evaluation of the  
372 minimum-jerk and minimum torque-change principles at the path, trajectory, and  
373 movement-cost levels. *Motor Control* 6, 69–83.
- 374 Madgwick, S., 2010. An efficient orientation filter for inertial and inertial/magnetic sensor  
375 arrays.
- 376 Madgwick, S.O.H., Harrison, A.J.L., Vaidyanathan, A., 2011. Estimation of IMU and MARG  
377 orientation using a gradient descent algorithm. *IEEE Int. Conf. Rehabil. Robot.* 2011,  
378 5975346.
- 379 Minami, I., Oogai, K., Nemoto, T., Nakamura, T., Igarashi, Y., Wakabayashi, N., 2010.  
380 Measurement of jerk-cost using a triaxial piezoelectric accelerometer for the evaluation  
381 of jaw movement smoothness. *J. Oral Rehabil.* 37, 590–5.
- 382 Minami, I., Zhao, N., Oogai, K., Nemoto, T., Whittle, T., Murray, G.M., 2011. A comparison  
383 between jerk-cost derived from a jaw-tracking system with that from an accelerometer. *J.*  
384 *Oral Rehabil.* 38, 661–7.
- 385 Nougier, V., Orliaguet, J.-P., Martin, O., 1993. Kinematic modifications of the manual  
386 reaching in climbing: Effects of environmental and corporal constraints. *Int. J. Sport*  
387 *Psychol.* 24, 379–390.

- 388 Phillips, K., Sassaman, J., Smoliga, J., 2012. Optimizing rock climbing performance through  
389 sport-specific strength and conditioning. *Strength Cond. J.* 34, 1–18.
- 390 Pijpers, J.R., Oudejans, R.D., Bakker, F., Beek, P.J., 2006. The Role of Anxiety in Perceiving  
391 and Realizing Affordances. *Ecol. Psychol.* 18, 131–161.
- 392 Richardson, M.J.E., Flash, T., 2002. Comparing Smooth Arm Movements with the Two-  
393 Thirds Power Law and the Related Segmented-Control Hypothesis. *J. Neurosci.* 22,  
394 8201–8211.
- 395 Sanchez, X., Boschker, M.S.J., Llewellyn, D.J., 2010. Pre-performance psychological states  
396 and performance in an elite climbing competition. *Scand. J. Med. Sci. Sports* 20, 356–63.
- 397 Sanchez, X., Lambert, P., Jones, G., Llewellyn, D.J., 2012. Efficacy of pre-ascent climbing  
398 route visual inspection in indoor sport climbing. *Scand. J. Med. Sci. Sports* 22, 67–72.
- 399 Schneider, K., Zernicke, R.F., 1989. Jerk-cost modulations during the practice of rapid arm  
400 movements. *Biol. Cybern.* 60, 221–30.
- 401 Seifert, L., Orth, D., Héroult, R., Davids, K., 2013a. Affordances and grasping patterns  
402 variability during rock climbing. In: Davis, T., Passos, P., Dicks, M., Weast-Knapp, J.  
403 (Eds.), *Studies in Perception and Action XII: Seventeenth International Conference on*  
404 *Perception and Action.* Psychology Press, Taylor & Francis, Estoril, Portugal, pp. 114–  
405 118.
- 406 Seifert, L., Wattebled, L., L'hermette, M., Bideault, G., Héroult, R., Davids, K., 2013b. Skill  
407 transfer, affordances and dexterity in different climbing environments. *Hum. Mov. Sci.*  
408 32, 1339–52.
- 409 Sibella, F., Frosio, I., Schena, F., Borghese, N.A., 2007. 3D analysis of the body center of  
410 mass in rock climbing. *Hum. Mov. Sci.* 26, 841–52.
- 411 Testa, M., Martin, L., Debû, B., 1999. Effects of the type of holds and movement amplitude  
412 on postural control associated with a climbing task. *Gait Posture* 9, 57–64.
- 413 Testa, M., Martin, L., Debû, B., 2003. 3D analysis of posturo-kinetic coordination associated  
414 with a climbing task in children and teenagers. *Neurosci. Lett.* 336, 45–9.
- 415 Wininger, M., Kim, N.-H., Craelius, W., 2009. Spatial resolution of spontaneous accelerations  
416 in reaching tasks. *J. Biomech.* 42, 29–34.
- 417 Winter, E.M., Eston, R.G., Lamb, K.L., 2001. Statistical analyses in the physiology of  
418 exercise and kinanthropometry. *J. Sports Sci.* 19, 761–75.
- 419 Yan, J., Hinrichs, R., Payne, V., Thomas, J., 2000. Normalized Jerk: A Measure to Capture  
420 Developmental Characteristics of Young Girls' Overarm Throwing. *J. Appl. Biomech.*  
421 16, 196–203.

- 422 Young, R.P., Marteniuk, R.G., 1997. Acquisition of a multi-articular kicking task: Jerk  
423 analysis demonstrates movements do not become smoother with learning. *Hum. Mov.*  
424 *Sci.* 16, 677–701.
- 425 Zampagni, M.L., Brigadoi, S., Schena, F., Tosi, P., Ivanenko, Y.P., 2011. Idiosyncratic  
426 control of the center of mass in expert climbers. *Scand. J. Med. Sci. Sports* 21, 688–99.
- 427