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# The effect of fatigue on climbing fluidity and hand movements

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**ABSTRACT**

In rock climbing, climbers use their arms to regulate their posture on the wall, which can lead to localised muscle fatigue. Evidence shows fatigue is the primary cause of falls, but little is known about how fatigue specifically affects climbing rhythm and hand movements. The present study examined climbing fluidity and hand movements on an indoor climbing wall before and after a specific fatiguing protocol. Seventeen climbers completed three repetitions of a challenging climbing route (21 on Ewbank scale) with different levels of localised arm fatigue. Climbers' movements were tracked using 3D motion capture, and their hand actions assessed using notational analysis. Seventy markers were used to create 15 rigid body segments and the participants' centre of mass. The global entropy index was calculated on the path of the participants' centre of mass. Climbers fell more often when fatigued, but there were no significant differences in hip jerk or global entropy index when fatigued. No significant differences were found between the number of exploratory or performatory hand movements with different amounts of fatigue. The results suggest that localised arm fatigue affects a climber's ability to prevent themselves from falling, but it does not specifically affect their fluidity.

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Rock climbing; movement; hand movement; fluidity; jerk

## Introduction

In most motor tasks, movements tend to become smoother, and more precise with experience (Seifert et al., 2018). In rock climbing, as climbers accumulate experience they tend to move with greater agility and more efficient climbing style (Sibella et al., 2007). Skilled climber's fluid movements have been equated to an oscillating pendulum (Cordier et al., 1996). Climbing routes may take several minutes to ascend (Watts, 2004), and the time limit in lead-climbing competition is 6–8 minutes. In this time the climber may experience acute bouts of neuromuscular fatigue—the inability to maintain a given force output (Giles et al., 2020; Girard & Millet, 2009; Lepers et al., 2008). Localised neuromuscular fatigue decreases the accuracy of movements (Forestier & Nougier, 1998), ability to produce force (Fryer et al., 2015; Giles et al., 2020; Laffaye et al., 2016) and

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localised neuromuscular fatigue has shown to reduce a climber's perceived and maximal overhead reach-to-grasp (Pijpers et al., 2007). In turn, this may increase exploratory and performatory hand movements when the climber is highly anxious (Pijpers et al., 2006). Exploratory and performatory hand movements in climbing are defined as holds that were (e.g., reach-to-climb) and were not used (e.g., reach-to-support) to help ascend a route (Pijpers et al., 2006; Seifert et al., 2018). The purpose of this study was to examine how fatigue affects hand movements during climbing and climbing fluidity.

Rock climbing is a complex form of locomotion, combining upper and lower limb movements with perceptual-motor exploration (Button et al., 2016; Seifert et al., 2017). For this reason, to understand how a climber is able to economically move through their environment, we must first explore a key factor that contributes to climbing fluidity—the perception and realisation of reach and grasping affordances. In ecological psychology, opportunities for behaviours are afforded or not by the environment (Gibson, 1979; Turvey, 1992; Wagman, 2008). Perception of affordances is a continual personal process shaped by previous (Pijpers et al., 2007) and present experiences (Higuchi et al., 2011). Even if features of the environment afford the same action to two climbers, one climber may perceive the affordance and the other may not. Moreover, when a participant's action capabilities suddenly change (e.g., carrying additional load or being fatigued), they may require a period of physical and perceptual recalibration to explore changes to their altered capabilities and regain perceptual accuracy (Mark, 1987).

Proffitt and colleagues (Bhalla & Proffitt, 1999; Proffitt et al., 1995) performed some of the most influential studies examining the link between fatigue and perceptual accuracy. They found that humans perceive environmental features like hill slant and distance as steeper or farther when centrally fatigued (e.g., after a long run). However, in climbing the major cause of failure is peripheral fatigue in the hands and forearms (MacKenzie et al., 2020; Michailov, 2014; Watts et al., 2000). It is unknown whether peripheral fatigue in the arms affects perceptual estimates of reaching during a climb in the same way that central fatigue affects estimates of hill slant. Pijpers et al. (2007) examined the influence of different levels of fatigue on maximal overhead reach-to-grasp. They found that both perceived and actual maximal reach-to-grasp only decreased at high levels of fatigue (e.g., rating of perceived exertion 18–20 on a 20-point scale), suggesting a functional fit between perceived and actual capabilities; however, the potential association between perceived and actualised reach-to-grasp and a climbing performance measure (e.g., movement fluidity or hand movements) was not explored.

Climbers use their hands both to climb and to explore their environment (Nieuwenhuys et al., 2008). Sibella et al. (2007) showed that in rock climbing skilled climbers touch fewer than three potential climbing holds prior to using a hold to move. In a series of studies Pijpers et al., 2006 showed that climbers who experienced high anxiety had a reduced perceived and actual reach-to-grasp height (Study 1), and this reduction in reaching capabilities could have contributed to the significant increase in exploratory and performatory hand movements (Study 2). However, the authors acknowledged in the third study that it was unclear to what extent this result was due to a more conservative climbing style or attentional narrowing associated with anxiety. In a follow-up study, Pijpers et al. (2007) showed that maximal fatigue (RPE 18–20) reduced the climber's perceived and actual overhead reach-to-grasp by 2–3 cm on average, but the link to hand movements was not explored.

Climbing fluidity is defined as the regular movement without saccades (Komar et al., 2020). Various methods have been used to assess climbing fluidity: quantifying the path of climber's centre of mass curvature by using the global entropy index (Sibella et al., 2007; Watts et al., 2021), harmonic analysis of hip acceleration (Cordier et al., 1996) or assessing hip jerk (Seifert et al., 2014). While insightful, many of these methods are limited. Assessing the curvature of a climber's centre of mass only provides information on the spatial structure of a climber's fluidity and ignores stoppages. In contrast, assessing a temporal fluidity metric such as harmonic analysis ignores hip displacement from the wall. Hip jerk is a valid indicator of movement fluidity (Seifert et al., 2014), as it assesses hip rotation and translation and can account for changes in hip displacement associated with different behaviours (e.g., postural regulation); however, it fails to account for the global path taken by the climber. Therefore, a comprehensive assessment of climbing fluidity may require combining two or more of the previously described methods. Previous work in climbing has shown that climbers take on average 2–7 minutes to scale a 20-m route consisting of 27 moves (Watts, 2004). During this time, they often sustain isometric contractions in the forearms, which causes acute bouts of fatigue. Fatigue presents a considerable challenge to a climber's movement fluidity as it is the primary cause of falls (Watts, 2004).

To date, most of the current literature on climbing fluidity has focused on the role of experience. While there is a growing body of literature examining the influence of fatigue on reach-to-grasp (Pijpers et al., 2007) and grasping capabilities (Watts, 2004), the potential association between to climbing fluidity is still unclear. Therefore, the aim of this study was to investigate the effect of fatigue on experienced climbers' movement fluidity and exploratory and performatory hand movements. It was hypothesised that fatigue would decrease climbing fluidity and increase the number of exploratory and performatory hand movements as climbers will search for and use closer holds.

## Methods

### *Participants*

Based on previous research (Sibella et al., 2007), a total of 17 climbers (16 males, 1 female) aged 20–40 years, volunteered to participate in the study. The climbers had above intermediate ability (i.e., +22 on the Ewbank climbing difficulty scale) with a minimum of 18 months continual climbing experience, climbing at least twice per week. All participants were healthy and injury free at the time of testing. Prior to the study participants signed a written informed consent, with approval provided by the participating institution's Human Ethics Committee. For the testing they wore sport clothing with climbing shoes, and a climbing harness.

### *Experimental setup*

Participants attended one 90-minute testing session. Climbers were required to ascend a route three times as fluidly as possible while experiencing different levels of fatigue—no fatigue (control), maximally fatigued, and sub-maximal fatigue (after 2 minutes recovery). Movement fluidity was defined as a smooth continuous movement, minimising

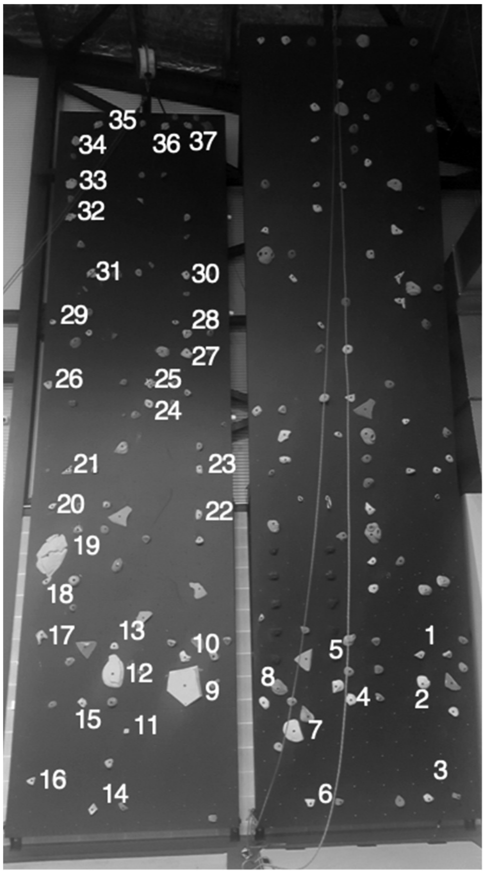


**Figure 1.** Location of 37 climbing holds for the climbing route.

stops and jerky movements. The route was created by a professional route setter (see Figure 1), using yellow climbing holds across two 2 × 7 m walls and was graded as 22 on the Ewbank climbing difficulty scale. Participants traversed 4 metres across two walls (10° and 0° incline respectively), before climbing up the 7-metre wall. After each climb, climbers rated their overall fatigue on the Borg (1982) rating of perceived exertion (RPE). Climbers were asked to rate the route difficulty before the fatigue protocol and at the end of the testing session.

For the fatigue conditions, participants completed one isometric hang for as long as possible on jug holds on a hang board (see Figure 2), maintaining 90-degree elbow flexion. Following the procedure by Mermier et al. (2000), the participants' elbow flexion was visually inspected by the chief investigator to ensure that the upper arm was perpendicular to the forearm. During the hang, the participants were given verbal encouragement, and told to adjust their position up or down as necessary. If the participant dropped too low they were instructed to pull up; if they were unable to pull up by the third instruction (e.g., up, up, up), the trial was terminated, and hang time was recorded. Once the participant let go or was unable to pull themselves up, they

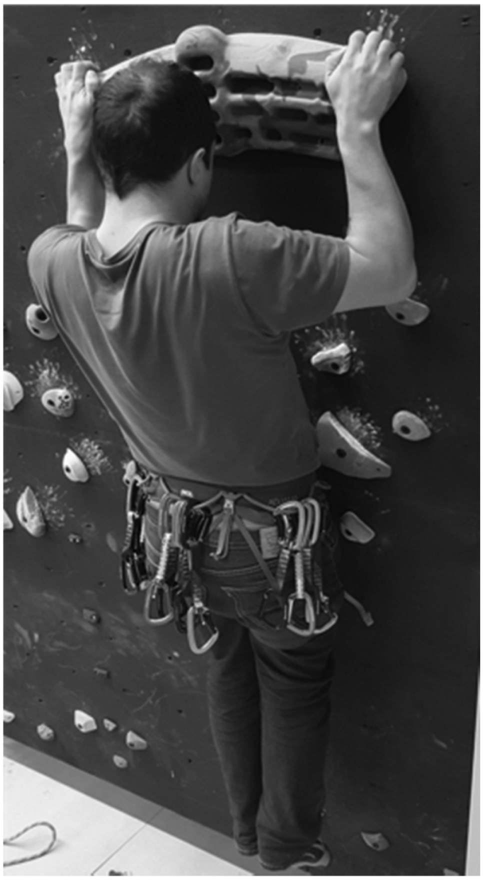

Figure 2. Maximal fatigue protocol where participants maintained 90-degree elbow flexion on a hang board.

immediately started climbing. No fatigue check was completed after the participant completed the hang.

## *Data collection*

All climbing movements were recorded using a VICON Motion Capture System (Oxford Metrics Ltd., Oxford, UK), with 21 infrared cameras sampling at 100 Hz, capturing the locations of 70 retro-reflective markers (see Figure 3). A total of 15 rigid body segments were created (head, thorax, pelvis, and left and right upper arms, forearms, thighs, shanks, hands and feet). Markers were attached to the anterior, medial, and posterior aspects of the skull, C7, T10, xiphoid process, sternum, anterior superior iliac spine, posterior superior iliac spine, iliac crest, acromion processes, medial and lateral epicondyles of humerus, lateral malleoli, and the posterior aspects of the calcaneus. A cluster of two tracking markers was placed on forearm, with three tracking markers placed on the posterior compartment of the upper arm, and anterior compartments of the thigh, and shank. Additional eight calibration markers were attached bilaterally to the lateral and

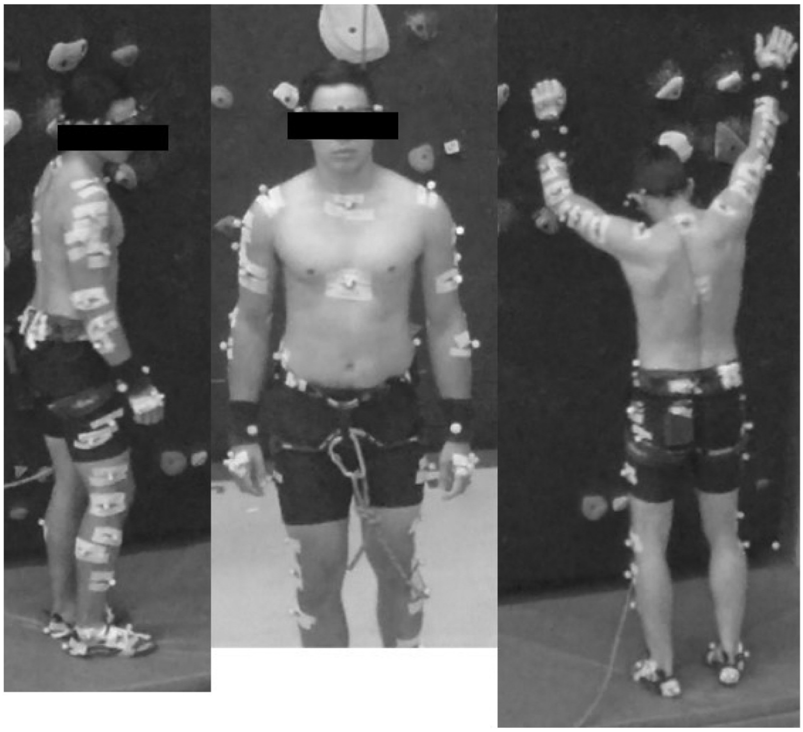

**Figure 3.** Retroreflective marker placement on climber from side, front and back.

medial aspects of the malleoli, and epicondyles of the femur—which were used to determine foot width and joint centre, respectively, and were removed prior to climbing commencement. Markers were fixed to the skin with adhesive tape and were further supported by medical tape. The anterior superior iliac spine and posterior superior iliac spine markers were fixed to the harness over the anatomical landmarks. A volume of $4.00 \times 7.00 \times 2.00$ m (X horizontal, Y vertical, and Z away from the wall, respectively) was calibrated using a wand as an experimenter was lowered by belay. A GoPro camera (Hero 5, San Mateo, California, USA) was placed 5 metres behind the climber facing the wall to record the climbers' movements.

### *Data analysis*

To ensure that no area outside of the intended route (e.g., area above holds 1 to 8 on the right wall) was incorporated into the climbing fluidity measures, the climb was divided into seven parts: four traverse segments and three vertical segments. The segments were defined as follows: section 1 – holds 1 to 17; section 2 – holds 18 to 21; section 3 – holds 21 to 27; section 4 – holds 27 to 30; section 5 – holds 30 to 32; section 6 – holds 32 to 34; section 7 – holds 34 to 37 (see Figure 1).

The three-dimensional positions of the reflective markers were reconstructed using VICON Nexus software (Oxford Metrics Ltd., Oxford, UK). All data were filtered using a 6-Hz low-pass Butterworth filter, with the cut-off frequency determined from residual analysis (Yu et al., 2010). The coordinates were imported into Visual 3D software (C-Motion, Inc., Germantown, MD, USA) to create a full-body model to calculate the centre of mass for each participant. Segmental coordinate systems (shank, thigh, forearm, upper-arm, head, and trunk) were created in accordance with (Wu et al., 2005). Full-body and segmental centre of mass were calculated for each participant for each trial.

### Climbing fluidity

Two measures of climbing fluidity were used; hip jerk and global index of entropy (GIE).

Hip jerk was calculated by examining the rate of change of acceleration of the climber's centre of mass. Hip jerk ($J_x^{GF}$) was defined as:

$$J_x^{GF}(T) = C \mathop{}_{0}^{T} \| x_x^{GF} \|^2 ds,$$

where C was a normalisation constant to make the quantity dimensionless (Hogan, 1984). Moreover, analysis of the variance of hip movement (amplitude) was calculated by quantifying the oscillation of the climber's centre of mass between each trail. Global index of entropy measures the amount of chaos versus order in a system and was calculated for the X, Y, and Z directions. The global entropy (H) was calculated by taking the logarithm of twice the length covered by the body centre of mass (LP) divided by the perimeter of the convex hull around the path (c). Global index of entropy (H) was defined as:

$$H = \ln \frac{2 * LP}{c},$$

where LP = CM path length, c = perimeter of the convex hull around LP. Jerk coefficient and global entropy index were calculated for each section of the climb for each climber. All statistical analyses were conducted using the lme4 (Bates et al., 2014) and lmerTest (Kuznetsova et al., 2017) packages in the R statistics program (R Core Development Team, 2016).

To understand how climbing fluidity was affected by the different levels of fatigue, we constructed linear mixed effect models using predictors of trial (no fatigue, maximal fatigue and sub-maximal fatigue respectively) and route sections as fixed effects and participant as a random effect. Jerk was modelled by examining the interaction between trial and section (Model 1: jerk ~ trial * section + (1| participant)). In a subsequent model, amplitude (Model 2: amplitude ~ trial * section + (1| participant)) was examined using linear mixed model. Global index of entropy was modelled for each section (Model 3: GIExy ~ section * trial + (1| participant); Model 4: GIEyz ~ section * trial + (1| participant); Model 5: GIEzx ~ section * trial + (1| participant)). Statistical significance was set at an alpha level of $p \leq 0.05$.

### Hand movements

To classify the participant's hand movements, video footage for 10 participants[1] was analysed frame-by-frame. For each trial, hand movements were classified as exploratory and performatory in accordance with Pijpers et al. (2006). We added a sub-category to exploratory hand movements called 'regrip', where the subject released and re-grasped the hold without using it for support. To determine reliability, video data was analysed by

**Table 1.** Number of performatory, exploratory and regrip hand movements and falls across the three fatigue conditions (means ± sd).

| | Performatory | Exploratory | Regrip | Falls |
|---|---|---|---|---|
| Non-Fatigue | 27.5 ± 2.12 | 1.6 ± 1.58 | 3.4 ± 3.1 | 0 |
| Fatigue | 21.1 ± 8.81 | 1.5 ± 1.78 | 3.3 ± 1.64 | 6 |
| Recovery | 23 ± 6.5 | 1.9 ± 3.03 | 3.8 ± 3.58 | 6 |

two different assessors. The first reviewer had numerous years of climbing experience, whereas the second review had no climbing experience. There was a 100% agreement between observers for performatory, exploratory and regrip hand movements. All hand movements were analysed using a chi-squared test with significance was set at an alpha level of $p \leq 0.05$.

## Results

No main effect was found in terms of fatigue for hip jerk ($F(_{1,28189078}) = 0.77$, $p = 0.38$). Similar results were found between fatigue conditions for global index of entropy; GIExy ($F(_{1,324}) = 0.002$, $p = 0.96$), GIEyz ($F(_{1,312}) = 0.008$, $p = 0.93$), GIEzx ($F(_{1,323}) = 0.00$, $p = 0.99$). A significant difference was found for hip jerk amplitude and route section ($F(_{1,384}) = 5.31$, $p = < 0.02$). A comparison between hip jerk amplitude and route sections showed significant difference in amplitude between sections 1 and 2 ($F(_{1,80}) = 11.04$, $p = < 0.001$) with higher amplitude scores in the first section (2.87) than the second section (2.00). Falls were analysed in a post-hoc test to determine the effect of fatigue on climbing success. Fatigue resulted in more falls 23% (4/17) falls versus no falls when the climbers were not fatigued. Climbers who fell in the fatigue trials also fell in the recovery trials, suggesting that 2 minutes was not enough time to sufficiently recover. Moreover, 75% of fall trials participants were in a 3-point of contact position and were moving. Interestingly, 62% (5/9) falls happened between holds 20 to 22, which required the climber to change body position from the left to the right side of the wall.

A chi-squared test did not show a difference in hand movements due to fatigue ($p = 0.60$)

### *Hand movements*

A chi-squared test did not show a difference in hand movements due to fatigue ($p = 0.60$). Performatory hand movements decreased from 27.5 to 21.1 and 23 for non-fatigued, fatigued and recovery, respectively. Exploratory and regrip hand movements decreased from non-fatigue to fatigue but increased when comparing non-fatigue to recovery (see Table 1). Analysis of rating of route difficulty revealed that climbers perceived the route to be 20 on the Ewbank Scale. Moreover, 53% of climbers (9/17) ratings of route difficulty did not change before and after the fatigue protocol, whereas 29% of climbers (5/17) increased their ratings of route difficulty. Of the climbers who fell, 50% of climbers (2/4) did not change their rating of route difficulty, whereas 50% of climbers (2/4) increased their ratings of route difficulty.

## Discussion and implications

The present study investigated the influence of fatigue on temporal and spatial measures of fluidity and hand movements in experienced climbers. The lack of difference due to localised fatigue in their arms suggests that experienced climbers maintain the same climbing style as when unfatigued. Moreover, no significant difference was found between the type of hand movements (i.e., performatory and exploratory) when climbers were unfatigued, fatigued, or partly recovered. Such findings did not support our hypothesis that fatigue would affect climbing fluidity and the number of exploratory hand movements.

Previous research has shown that hip jerk (Seifert et al., 2014) and geometric entropy (Watts et al., 2021) reduce as a climber becomes familiar with a route and that fatigue contributes to a decrease in movement fluidity (Cortes et al., 2014). Perhaps surprisingly, our results do not support these findings although the climbers experienced maximal fatigue and climbed the same route three times. It is possible that the holds used may not have required considerable contribution from the forearms (Amca et al., 2012). As the legs are used to support body mass (Quaine et al., 1997), climbers may have compensated for arm fatigue by using their legs more. The route may not have been sufficiently difficult as the climbers judged the route to be a 19 on the Ewbank scale, which was well within their capabilities. It is possible that the climbers were not sufficiently fatigued to elicit any changes, but this seems unlikely since 23% of climbers fell at least once whence fatigued. Moreover, the route was primarily comprised of pinch and open grip holds, which do not require much contribution from the forearms when compared to crimp and 2-finger grips (Saul et al., 2019; Watts et al., 2008). It is also possible that the arms have a minimal contribution to climbing fluidity, as they control posture and position, whereas the legs support the body mass (Quaine et al., 1997), suggesting that fatigue in the legs may have a greater effect on climbing fluidity.

The results also suggest that a climber's hand movements were not affected by different levels of fatigue. It could be argued that the climbers were familiar with the route after the first ascent (Hacques et al., 2021) and that local forearm fatigue was not adequate to elicit exploratory behaviours. Examination of the ratio of performatory to exploratory hand movements suggests the climbers seldom engaged in exploratory movements. While Pijpers et al. (2006) found that exploratory hand movements increase in high-anxiety conditions, it appears that fatigue does not induce similar increases. It is also possible that the climbing holds were placed so close together that when the climber was fatigued the average inter-hold distance was still within their altered action capabilities. Additionally, climbers did not have to use all of the yellow holds in the climb; therefore, it is likely that the route invited shorter reaches (hold 25 to 27) instead of longer reaches (26 to 27). Moreover, it is possible that maximal localised fatigue affects a climber's ability to remain in contact with a hold (Watts et al., 2008; Watts, 2004) and does not cause attentional narrowing that affects the realisation of affordances (Pijpers et al., 2006).

Currently, most of the climbing literature (Seifert et al., 2017; Sibella et al., 2007) is focused upon describing climbing behaviours through measures of spatial (and occasionally temporal) fluidity. While these studies have provided valuable insight into how climbers move, not much attention has focused on how these measures change when fatigued. Our results suggest that despite the fatigue experienced by the climbers, they were able to maintain the same climbing style; however, climbers only experienced localised muscular fatigue to the forearms. From a practical perspective, climbing requires contribution from both the arms and legs to move, therefore future studies should examine the effect of whole-body fatigue on climbing fluidity. Moreover, as previously discussed it is likely that the holds used in the study may not have been spaced far enough to elicit exploratory or have grips that grips that required much contribution from the forearms. Of the climbers who fell, the notational analysis revealed that falls were typically experienced around holds number 20 to 22 when attempting to move from the left side to the right side of the wall. Moreover, when climbers fell, 75% of them were in a 3-point contact. This suggests that climbers may have had issues regulating posture during movement as they were either reaching out to make their next move or they were moving an arm or leg to return to 4-points of contact with the wall. Climbers appeared to engage in some exploratory behaviour (visually scanning nearby holds and haptically exploring holds) in the moments leading up to the fall; however, we were unable to quantify these behaviours and further analysis will be needed.

## Limitations

While the study examined the effect of fatigue states on climbing performance, there are some limitations which may have affected the results. Firstly, no objective fatigue manipulation check was used in the study. While there are ways to objectively measure fatigue (e.g., hand grip dynamometry, EMG) we believe that the time taken to complete these measures would have affected the results. As all of the participants were very experienced rock-climbers, they would have experienced physiological adaptations that aid recovery. Moreover, the fatigue conditions were presented in a fixed-order to replicate partner climbing, where it is common for a climber to experience maximal (or near maximal) fatigue and only have a few minutes to recover while their partner climbs.

## Conclusion

In this study, we examined the influence of different fatigue conditions on climbing fluidity and hand movements. Overall, climbers were able to maintain climbing fluidity whether unfatigued, fatigued or partly recovered. Secondly, no difference was found between fatigue states and either exploratory or performatory hand movements. One important finding from this study was that localised forearm fatigue induced by hanging was not sufficient to change experienced climbers' movement fluidity and their exploratory behaviours.

## Note

1. Some video footage was corrupt, and complete video data was only available for 10 participants.

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