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SYSTEMATIC REVIEW

Coordination in Climbing: Effect of Skill, Practice and Constraints Manipulation

Dominic Orth[1,2] · **Keith Davids**[3,4] · **Ludovic Seifert**[1]

Abstract

Background Climbing is a physical activity and sport involving many subdisciplines. Minimization of prolonged pauses, use of a relatively simple path through a route and smooth transitions between movements broadly define skilled coordination in climbing.

Objectives To provide an overview of the constraints on skilled coordination in climbing and to explore future directions in this emerging field.

Methods A systematic literature review was conducted in 2014 and retrieved studies reporting perceptual and movement data during climbing tasks. To be eligible for the qualitative synthesis, studies were required to report perceptual or movement data during climbing tasks graded for difficulty.

Results Qualitative synthesis of 42 studies was carried out, showing that skilled coordination in climbing is underpinned by superior perception of climbing opportunities; optimization of spatial–temporal features pertaining to body-to-wall coordination, the climb trajectory and hand-to-hold surface contact; and minimization of exploratory behaviour. Improvements in skilled coordination due to practice are related to task novelty and the difficulty of the climbing route relative to the individual's ability level.

Conclusion Perceptual and motor adaptations that improve skilled coordination are highly significant for improving the climbing ability level. Elite climbers exhibit advantages in detection and use of climbing opportunities when visually inspecting a route from the ground and when physically moving though a route. However, the need to provide clear guidelines on how to improve climbing skill arises from uncertainties regarding the impacts of different practice interventions on learning and transfer.

Key Points

Skilled climbing performance is characterized by smoothness (organization of actions around minimization of jerk) and fluency (optimal linking of sub-movements in the spatial and temporal dimensions) in movement dynamics and hand-hold reaction forces.

Perceptual and movement-related adaptations, including gaze behaviour, limb activity and postural adjustment, appear to be optimized in elite climbers to support smoothness and fluency. Research priority should be placed on observing perception and movement during climbing tasks and determining their relationship to skilled climbing performance.

Scientists and coaches should interpret exploratory behaviour as a potential indicator of learning. Future research should determine if interventions that improve skill in climbing can be designed by manipulating task and environmental properties on the basis that they induce exploratory activity.

✉ Dominic Orth
dominic.orth1@univ-rouen.fr

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

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

[3] Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, UK

[4] FiDiPro Programme, University of Jyväskylä, Jyväskylä, Finland

1 Introduction

Climbing is a physical activity and sport, which encompasses disciplines including ice climbing (where hand-held hooks and specialized footwear are used to climb ice formations), mountaineering (mountain ascent), traditional climbing (ascent of rock faces during which the climber places and removes protective bolts), sport climbing (ascent of artificial and natural faces; the main forms of protection [bolts] are pre-placed and permanent) and bouldering (ascent of artificial and natural faces of restricted height, not requiring the use of rope); see Lockwood and Sparks [1] and Morrison et al. [2] for details. Each discipline can be further delineated into subcategories based on the environment, regulations, equipment, risk and norms. For example, 'on-sight' climbing is where the climber has not physically practised on the route but has had the opportunity to observe the route from the ground (referred to as 'route preview'). 'Red-point' climbing refers to when the individual has already physically practised on a route. Other common permutations include 'leading', which refers to when the climber secures their ascent at bolts throughout the route, using a safety rope fitted to a harness worn at the hips. 'Top-rope' means the rope is passed through a bolt at the top of the route prior to undertaking the ascent, and there is no need to secure the ascent during the climb. Because of the extensive range of climbing disciplines, a central goal in climbing is to improve performance in intended contexts (such as a competition or an outdoor environment) through experience gained in training situations.

Traditionally, in climbing, factors that affect performance are reduced to a single grade value, such as the French Rating Scale of Difficulty (F-RSD), which is used extensively in Europe; the Yosemite Decimal System (YDS), which is used in the USA; and the Ewbank System, which is common to Australia, New Zealand and South Africa. Rating scales are used to classify the route difficulty and ability level of the climber [3]. The F-RSD, for example, is an alphanumeric value ranging from 1 to 9b+, where, according to Draper et al. [3], a male is considered elite if he successfully climbs a route graded between 8a+ and 8c+. Rating scales are meaningful as a general training aid and for experimental purposes (for example, Table 1 shows how scales can be converted to statistically usable, number-only systems, such as the Ewbank and Watts scales). In reality, there are inherent limitations in using rating scales to understand climbing skill, because, as Draper et al. [3] highlight, an extensive range of factors can affect climbing performance.

From a skill acquisition perspective, the ability to climb a route is based on how effectively individuals can coordinate perceptual–motor behaviour to meet interacting constraints on performance (constraints referring to interacting task, individual and environmental factors) [4]. Furthermore, factors that constrain coordination during training have a significant role in an individual's capacity to adapt successfully to constraints on performance [5]. While climbing performance has been addressed by different scientific disciplines—including injury risk [2, 6–13], testing [3, 14], physiology and anthropometry [15, 16], strength and conditioning [17], therapeutics [18] and engineering design [19, 20]—the existing reviews taking a skill acquisition approach have been limited in scope (and included coordination of hand-to-hold-surface interactions [21, 22] and pedagogical approaches [23, 24]). A comprehensive evaluation of constraints on coordination in climbing is needed for understanding of what adaptations support skilled coordination and how to design training contexts that support its transfer. Therefore, the aims of this systematic review were to provide an overview of the constraints on skilled coordination in climbing and to explore future directions in this emerging field (e.g. http://www.climbing.ethz.ch/).

Acquisition of skill involves adaptations in the structural and functional characteristics of an individual in relation to factors that influence coordination during practice or performance [25]. Similarly, successful transfer of skills (in contexts that differ from training) is highly dependent on prior experience and the level of expertise developed [26–28]. The constraints-led approach (proposed by Newell [29–31]) has proven to be a powerful framework for

Table 1 Examples of current rating scales used to classify route difficulties and climbers' ability levels (adapted with respect to Draper et al. [3])

Ability group	French Rating Scale of Difficulty		Yosemite Decimal System		Ewbank System		Watts Scale	
	Male	Female	Male	Female	Male	Female	Male	Female
Lower grade	1 to 5	1 to 5	5.1 to 5.9	5.1 to 5.9	9 to 17	9 to 17	0 to 0.75	0 to 0.75
Intermediate	5+ to 7a	5+ to 6b+	5.10a to 5.11d	5.10a to 5.11a	18 to 23	18 to 22	1.00 to 2.50	1.00 to 2.00
Advanced	7a+ to 8a	6c to 7c	5.12a to 5.13b	5.11b to 5.12d	24 to 29	22 to 27	2.75 to 4.00	2.25 to 3.50
Elite	8a+ to 8c+	7c+ to 8b+	5.13c to 5.14c	5.13a to 5.14a	30 to 34	28 to 32	4.25 to 5.25	3.75 to 4.75
Higher elite	9a to 9b+	8c to 9b+	5.14d to 5.15c	5.14b to 5.15c	35 to 38	33 to 38	5.50 to 6.25	5.00 to 6.25

identifying important factors that shape coordination during performance and throughout practice and development [25, 32, 33]. Interacting constraints on climbing behaviours include the individual (e.g. arm-span, fingertip strength and recovery [34]), the task (required speed [35], lead-rope versus top-rope [36]) and the environment (wall slope [37], hold characteristics [22]). These constraints mutually interact during performance to place boundaries on an individual's coordination behaviours [25].

Skilled coordination patterns in climbing can be measured by estimating how individuals perceive and use information during route preview and climbing [23, 26, 38, 39]. During route preview, climbers visually inspect a route from the ground to consider how to coordinate their actions with respect to important surface properties of the holds and wall [38, 40, 41]. During climbing, individuals coordinate their actions with respect to features of the climbing surface by forming relationships between limbs [42] and surface properties [43, 44], which are regulated over time to complete the route [45]. Coordination can also be classified across different levels: coordination between limbs is called intra-personal coordination, coordination between individuals is called inter-personal coordination and coordination between individuals and their environment is called extra-personal coordination [46]. Understanding coordination in climbing requires assessment of spatial and temporal relationships that emerge between an individual's perceptual and movement systems (intra-personal) and surface features of a climbing environment (extra-personal). Measures relevant to understanding coordination during climbing tasks can therefore include forces applied at hand-holds [44, 47], limb [42] or whole-body kinematics [39, 43, 48], neuromuscular activation [49], gaze position [50], cognitions and perceptions [40, 51, 52].

From an experimental design perspective, coordination can be understood through four broad approaches:

1. The coordination behaviours of expert individuals who, through extensive experience and practice, have adapted unique characteristics that enable them to perform under exceptionally difficult levels of constraint [53] (such as in competition [54] or extreme environments [51]) can be observed.
2. Contrasting coordination behaviours of performers on the basis of expertise level [55] can determine behaviours that can be developed through training or feedback [56, 57] (such as in some recently published articles [41, 43, 44, 51, 58]).
3. Practice effects can also provide insights into how coordination evolves and what factors influence the rate, retention and transfer of skill acquisition [31, 59–61].
4. Coordination and its acquisition can be understood by observing the effect of manipulating different environmental and task constraints (such as changing hand-hold characteristics [62, 63]).

This review provides an overview of how coordination in climbing can be studied at the level of the individual and their performance constraints, and in what ways coordination and constraints influence climbing performance. The first step was to uncover the existing data from perceptual and/or motor behaviours observed during actual or simulated climbing tasks. Studies are discussed across four sections based on their contribution to understanding: coordination in elite climbers; the effect of skill on coordination; the effect of practice on coordination; and the impact of manipulating task and environmental constraints on coordination.

2 Methods

2.1 Search Strategy

The Medline and Embase databases were searched for published primary sources. Key words for climbing were pooled via the Boolean operator 'OR' (including rock, ice, mountaineering, bouldering, artificial, top-rope, lead-rope, speed, mixed, indoor, outdoor, preview, route finding, slope) and combined with 'climbing' (via 'AND'); and were then combined via 'AND' with pooled keywords related to skill (skill, transfer, performance, ability, expertise, novice, intermediate, advanced), measures of interest (dynamic, force, kinematics, kinetics, perception, action, cognition, behaviour, centre of mass, recall, gaze, vision, motor, coordination, feet, hands, grasp, movement pattern) and intervention (intervention, pedagogy, feedback, constraint, coaching, learning, practice). Full texts from the earliest available record up until February 2014 were retrieved, and citations were scrutinized by hand for additional studies.

2.2 Inclusion Criteria, Data Extraction and Data Management

The primary inclusion criteria for this review required (a) studies to measure perceptual, spatial and/or temporal characteristics of the climber during interactions with a wall surface during an ascent, or during or immediately following preview of a route; and (b) that the outcomes were interpreted by authors with respect to their impact on performance (i.e. positive, neutral or negative for performance). A secondary criterion was that the task needed to involve a route that was theoretically gradable according to an existing climbing discipline. The purpose of the secondary criterion was to differentiate articles where the goal of the task was not to get to the end of the route but, for example, the task consisted of participants adopting an instructed posture. The logic behind this exclusion criterion was that previous studies have demonstrated that task goals have important impacts on skilled coordination [64, 65]. Studies were recorded in separate tables. Data on sample characteristics, the nature of the interventions, the task, observations and significant effects (as reported by the study authors) were extracted and included in summary tables. Studies not reported in the English language or from unverifiable sources were excluded.

3 Results

A total of 190 articles were located through database searching ($n = 145$) and scrutiny of reference lists ($n = 45$). After duplicate removal ($n = 24$), 166 article titles and abstracts were screened, leaving a total of 63 articles, which were assessed for eligibility using the inclusion criteria. Ineligible articles ($n = 21$) were excluded for various reasons (see Fig. 1); of these, 15 studies fulfilled the primary criteria but were excluded for not fulfilling the secondary criteria (notably, [47, 63]) (experiment 1 [66]) [67–77]. Qualitative synthesis of the remaining 42 studies was carried out (see Fig. 1 for an overview of the selection process). Specifically, 42 separate articles [24, 26, 36, 38–45, 48, 50–52, 54, 55, 58, 62, 66, 78–99] fulfilled the primary and secondary criteria and involved 45 separate experiments.

Studies were then organized into four sections for discussion on the basis of whether they involved an elite climber sample, compared skill effects, reported trial effects or compared different conditions (environmental or task-related); see Table 2 for an overview with some example studies. More specifically:

1. Seven studies reported data related to elite climbers (as per the categories outlined by Draper et al. [3]) [43, 54, 82, 83], F-RSD (a scale that ranges between 1 and 7 [51]) grades for ice climbing of 6–7, and World Cup rankings under 50 [44, 98].
2. Twenty-seven studies compared groups of climbers on the basis of different ability levels [24, 26, 38–44, 48, 51, 54, 58, 62, 79–83, 87, 88, 90, 94, 97–99].
3. Eleven studies reported practice effects [24, 38, 39, 44, 45, 52, 79, 80, 90, 95, 96]).
4. Twelve studies compared the effects of different environmental manipulations [50, 62, 66, 78, 82, 83, 89, 91–93, 95, 96]), while 12 studies compared the effects of changing the instructions or rules [36, 40, 41, 44, 52, 55, 66, 84–86, 90, 99]).

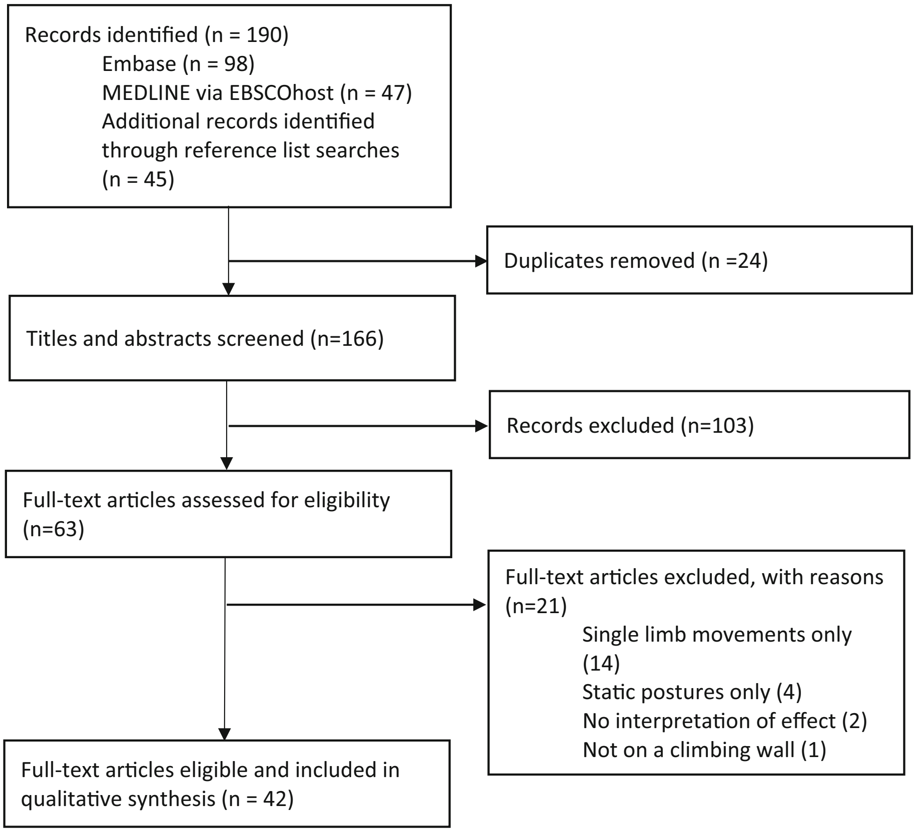

Fig. 1 Flowchart of the selection process for inclusion of articles in this systematic review

Table 2 Characteristics of constraints on climbing tasks uncovered through the review procedure

Constraint	General	Specific
Task	Instruction	Required climbing speed [92]; use of specific gripping technique [52], reaching action [68], postural position [47] and/or movement pattern [43]; attending to additional foci [84]; self-preferred [94]; competition event [54]; application of maximal force [67]
	Route safety demands	Lead-rope (existing bolts) [36]; top-rope [66]; bouldering (safety mats, no-rope) [98]; roped
	Route practice	On-sight [54]; second attempt [24]; after practice [45]
	Route preview	With preview [54]; without preview [41]; flash (demonstration by a peer) [52]
	Specialized equipment	Ice tools [74]
	Outcome performance objective	Competition [98]; best time possible [99]; memory recall [38]; attempt to complete route (no other specific instruction) [96]; movement simulation [43]; estimation of behavioural opportunities [40]; route finding [86]
	Difficulty level	Very easy; lower grade; intermediate; advanced; elite; set relative to climber's ability [40]
Environment	Route properties	Artificial [95]; ice [26]; rock [24]
	Weather	Indoors [95]; outdoors
	Context	Competition [98]; climbing gym [90]; natural surface [26]; specialized laboratory surface [67]
	Wall	Slope [100]; height [66]
	Holds	Number of edges [95]; edge depth [62]; shape complexity [78]
	Route design characteristics	Horizontal and vertical inter-hold distances [90]; crux points [96]; continuous difficulty [97]; escalating difficulty within route [38]; rest points [58]
Individual	Psychological	Anxiety [36]
	Ability level	No experience [52]; lower grade [26]; intermediate [41]; advanced [38]; elite [43]
	Structural and functional	Anthropometric [48, 90]
	Developmental	Age [76]; previous climbing genres [26]

Notably, 14 studies were published in non-indexed peer-reviewed sources [24, 44, 58, 62, 81, 82, 86–90, 94, 96, 99] and were included for the purpose of exploring future research directions.

4 Discussion

4.1 Characterizing Elite Climbing Skills

Elite climbers have been observed in competitive on-sight, lead-rope [44, 54] and bouldering contexts [98]; in top-rope, submaximal ice climbing [51]; in top-rope laboratory conditions [43]; and in an isolated movement problem [83].

4.1.1 Coordination of Posture When Reducing the Area of Support

Research has shown that postural constraints are major factors driving adaptations in the static and dynamic coordination behaviours of climbers. A climber's postural stability is constantly under threat because the available surface area over which to support the body mass is limited [47, 68]. This challenge can be further compounded by a surface slope [70, 100], relative sizes of supports [69] and distances between supports [63]. When transition from a static four-limb support coordination mode to a three-limb support mode is required [72, 77], elite climbers maintain postural stability through anticipatory redistributions in weight, supporting adaptations to the slope [70, 100], hold size [63, 75, 76], hold distribution [63, 75, 76] and initial posture [63, 71].

In transitioning from a static state to a dynamic state, when a new surface hold must be grasped, this threat to postural stability also shapes the emergence of coordination of the reaching action where an emphasis is placed on movement preparation to reduce the amount of time spent in the three-limb coordination mode [68]. This is also the case when the size of the hold is reduced [47]. When multiple reach and grasp movements are organized sequentially [47, 68, 69], movement time continues to be faster even if hold size is reduced [47], but, additionally, attentional demands during regulation of the terminal phase of the first reach and grasp action are increased [68], suggesting that actions required later in a movement sequence influence the climber's cognitions during the current activity.

Supporting the above findings observed in non-route-finding tasks, White and Olsen [98] undertook a time–motion analysis of elite climbers during a national bouldering competition, revealing a minimization of time spent reaching to grasp holds relative to other states. Specifically, in trials that took on average 29.8 s (SD = 1.7), 22.3 s (SD = 2.1) was spent in a dynamic state (being in contact with a hold at the same time as a hip movement emerged); 7.5 s (SD = 1.6) was spent in static mode (in contact with a hold but with no hip movement), and it was reported that only 0.6 s (SD = 0.1) was spent reaching for holds. Considering the large amount of time spent in static and dynamic states (similar to the study by Billat et al. [78]), the specific coordination behaviours exhibited during these organizational states should have an important role in climbing performance. For example, although more experienced climbers can spend similar amounts of time in static states, in comparison with less experienced climbers, this time reportedly involves more active resting (shaking the wrist or chalking) [58], and future research should be directed towards understanding the functional aspects of static and dynamic modes of coordination.

4.1.2 Coordination of Actions When Climbing Through a Route

Zampagni et al. [43] investigated whether adapted coordination strategies emerge during continuous climbing, comparing centre-of-mass (COM) positioning and hand-hold reaction forces of a group of experienced climbers (advanced–elite) relative to a group of inexperienced climbers. Participants top-roped a wall made up of large, uniform holds (13 cm in height × 16 cm in width × 12 cm in depth), arranged in two parallel columns (separated by 50 cm horizontally and 57 cm vertically). Participants were instructed to climb using the same coordination sequence to pass between holds and maintain a tempo of 4 s per climb cycle (one climbing gait cycle corresponded to a right foot lift–left foot and trunk lift–right hand lift–left hand lift). Experienced climbers exhibited a significant tendency to keep the COM further from the wall during both static and dynamic climbing phases and displayed larger lateral oscillations in COM positioning when taking new holds [43]. It was suggested that a far position from the wall would require less organization by the nervous system for regulating counterbalancing torques and that an improvement in joint mobility would be gained from this approach. It was also suggested that by laterally oscillating the COM, climbers exploited mechanical energy to take advantage of more efficient force/length relationships in muscles [43].

Russell et al. [94] also addressed how climbers coordinated posture with the climbing surface, suggesting that by positioning the COM further from the wall, climbers were able to maintain an arm-extended position for longer during vertical displacement. In experienced climbers (intermediate level), this coordination mode resulted in a more functional force–length relationship in the biceps brachii (a flexor). Conversely, the more flexed arm positions adopted by inexperienced climbers favoured the use of the triceps brachii (an extensor). Although total work was the same between the adapted postures, the experienced climbers tended to minimize the magnitude of the force generated relative to their own maximum force-generating capacity, while inexperienced climbers minimized the magnitude of the overall force [94] and were hence less efficient. Similarly, in static postural tasks, skilled climbers have been shown to evenly distribute forces across hand-holds when coordinating self-preferred postures in comparison with experimenter-imposed arm-flexed positions [94]. These studies suggest that for estimating the efficiency of a climber's static and dynamic movements, the angular magnitudes at the elbow joints can provide useful information. Interestingly, the instructions in the study by Russell et al. [94] differed from those imposed on participants by Zampagni et al. [43], allowing the participants to sequence movements in the climbing cycle as they liked. As a consequence, different climbing cycle patterns were spontaneously coordinated between participants. However, the impact of different climbing gaits were not tested [94], and this aspect would be of interest for future research. Of additional concern, limitations proposed in both studies [43, 94] were that hold characteristics were very easy relative to the ability level of the participants. It is possible that hold configurations and sizes encountered under more challenging constraints might mean that sitting away from the wall is not an optimal strategy for conserving energy or moving through the route, requiring different coordinated behaviours.

Indeed, in contrast to the findings discussed above, results reported by Fuss and Niegl [44] and Fuss et al. [62] showed that to increase friction at a hold surface, climbers can reduce tangential force only by moving their COM closer to the wall. Fuss et al. [62, 83] also evaluated reaction forces during dynamic climbing. In their study, participants with a range of ability levels (including an elite climber) were required to jump and grasp a hold scaled across six different vertical heights. Successful attempts involved jumping higher than necessary to complete the hold and grasping it before the dead point (defined as when the COM transitions to returning to the ground). Increasing the distance of the COM from the wall during this technique had the effect of increasing the hip angle, reducing the effective height of the climber, signifying that a higher jump was needed to reach the hold. Fuss et al. [62] also examined how the slope of a hold, when systematically reduced from the horizontal, influenced coordination of hold forces. At specific values, a transition from applying horizontal pulling forces at the hold to applying horizontal pushing forces to use the hold was exhibited (22° from the horizontal in less experienced individuals and 34° in more experienced climbers). The latter coordination strategy indicated that the hips were moving away from the wall in a qualitatively different manner in order to use the hold at more extreme angles [62]. Transitional behaviour is of tremendous interest because it suggests the potential for identifying control parameters underpinning the emergence of a new coordination mode [101]. It is possible, for example, that combining dynamic states with different hand-hold configurations or sizes may be a way of determining the limits of an individual's movement pattern stability.

4.1.3 Rate of Adaptation to Environmental Constraints

Of interest in understanding expertise is coordination of forces at hand-holds and how this can contribute to climbing performance. Fuss and Niegl [44] evaluated time series of reaction forces applied to a hand-hold equipped with three-dimensional piezoelectric transducers during on-sight lead competition ascents, examining mechanical parameters in detail. In the first experiment, three functional phases of hold interactions were highlighted [44]. The first phase corresponded to a 'set-up' phase, where resultant force variability was considered as haptic exploration to position the fingers and hand. The 'crank' phase involved applying force for the purpose of lifting the COM. Finally, the 'lock-off' involved a combined period where the load was transferred to another limb at the same time as the hand began to move to another hold. Notably, a number of mechanical parameters during hold interactions were evaluated, showing that low force (maximum, mean), low contact time, low impulse (normalized), a high friction coefficient (maximum, mean), a low Hausdorff dimension (level of chaos) and a high level of smoothness were interpretable performance parameters responsive to practice [44], suggesting that, through experience, individuals tend to optimize these parameters.

In experiment 2, Fuss and Niegl [44] compared a lower-ranked climber (with a World Cup ranking of >50) with an elite counterpart (with a World Cup ranking of <20) on the different phases of contact (set-up, crank, lock-off). The lower-ranked climber spent a longer period in set-up, as well as exhibiting a prolonged lock-off phase. In fact, this climber also fell because of an inability to organize a high enough friction coefficient [44]. In contrast, the set-up phase for the elite climber was almost non-existent, suggesting that the climber either was in a better position to immediately use the hand-hold or had an advanced understanding of how to use the hold, not requiring exploratory behaviour.

A reduction in parameters that measure overt exploratory behaviour in elite climbers has also been revealed at the limb level by Seifert et al. [51]. Elite ice climbers climbing a moderately difficult route (with an F-RSD grade for ice climbing of 5+) were evaluated on parameters related to exploration and sources of information relied upon. Multimodal sources were found to contribute to coordination of action (see also Smyth and Waller [102]). Specifically, elite climbers reported that the relationships between structural features of the climbing surface and behavioural opportunities were located through a visual search and through auditory perception (sounds of hook–ice interactions) and haptic perception (vibration) [51]. These informational constraints emerged in conjunction with performance data showing a continuous vertical ascent and a 1:1 ratio in ice hook swinging relative to implementing definitive anchorages. In contrast, inexperienced ice climbers displayed very slow ascent rates and a ratio of about three swings to every definitive anchorage, suggesting an inability to perceive climbing opportunities for ascent support in an ice fall [51]. These less experienced individuals also reported that their search was primarily visual and pertained to structural features of the ice surface (such as the size of holds).

4.1.4 Psychological and Behavioural Relationships to Climbing Performance

Psychological factors are an important individual constraint in climbing [54, 103, 104], and their impact on coordination behaviours has been previously raised [37, 55, 84, 105, 106] but rarely measured directly. Sanchez et al. [54] reported movement data captured during a climbing championship for the same on-sight lead route. The frontal plane geometric index of entropy (GIE) and climb times were analysed at the first two sections of a three-section route and at two crux points (crux points refer to parts of a climb that are more difficult than the overall average). The GIE provides a measure of how 'chaotic' a movement trajectory is, and measures indicate the fluency of a curve, where the higher the entropy, the higher the disorder of the system, whereas a low entropy value is associated with a low energy expenditure and greater climbing fluency. Sanchez et al. [54] found that better performance outcomes correlated positively with high levels of somatic anxiety but only in combination with a positive affect. More expert climbers also showed slower climb times within a crux point. While no relationships between performance outcomes and the GIE were found, an association between pre-performance emotions and the GIE was reported. Similar to data reported by Pijpers et al. [91, 93], involving inexperienced climbers, higher anxiety appeared to increase entropy during climbing, reflecting a potential reduction in climbing efficiency.

Similarly, Hardy and Hutchinson [36] assessed climbers' performance, using the Climbing Performance

Evaluation Inventory (CPEI). Specially, the CPEI is relevant in this discussion because it includes ratings on efficiency in equipment use, gracefulness in movement, economy of effort, ability to read the route, and levels of focus and control. Using these measures, Hardy and Hutchinson [36] showed that anxiety induced by leading at the limit of ability could have a detrimental effect on performance. However, if climbers perceived experienced anxiety in a positive way, they did not show performance decrements in terms of CPEI ratings. Draper et al. [55] also found that climbers who successfully completed either lead-rope or top-rope routes reported higher levels of confidence. This study also measured the time taken to reach seven successive positions in the route, showing that successful climbers tended to surpass early sections faster than those who fell. Interestingly, successful climbers had higher overall oxygen consumption, suggesting they had a reduced anabolic demand in comparison with climbers who fell, possibly signifying a different climbing style. Additionally, despite the overall group consisting of climbers within a similar ability level, as shown in small standard deviation data in the reported Ewbank scores (on-sight was 18.4 ± 0.5 and red-point was 20.7 ± 1.1, both within an intermediate standard), their years of experience were significantly different (the successful group's climbing age was 4.8 ± 3 years, whereas the unsuccessful group's climbing age was 2.2 ± 0.5 years). This finding suggests that practice volume supports climbing performance, even if the absolute ability level is no different, with data implying that the behaviour and perhaps the psychology of more experienced individuals during the ascent are important factors.

4.2 Skill Effects in Climbing: Implications for Understanding Preview and Route-Finding Performance

As highlighted earlier, skill differences can uncover important adaptations, many of which can appear counterintuitive. Skill differences discussed in the following section pertain to preview tasks [38, 40] and relationships between coordination and climbing fluency [26, 39, 45, 48, 79, 80, 95].

4.2.1 Acquisition of Climbing-Specific Skill Supports Preview Performance

Competition can involve on-sight climbs, and it is tacitly assumed that an ability to determine effective route planning, prior to climbing, can improve performance; however, this remains to be shown conclusively [41]). Boschker et al. [38] and Pezzulo et al. [40] raised questions related to the ability to recall information after preview, suggesting that because climbers undertake a movement simulation (i.e. practise the route mentally) during route preview, recall of the climbing route is enhanced. In both studies [38, 40], climbers were required to reproduce, after a viewing period, features of the climbing route (including the positions [38, 40] and orientations [38] of holds). Boschker et al. [38] compared performance across an inexperienced subgroup, a lower grade–intermediate group and an intermediate–advanced group. The advanced subgroup recalled more about the route (set at an intermediate level) and were sensitive to route properties, with their initial recall efforts based on the most difficult part of the route [the route increased in difficulty with height] (also shown by Grushko and Leonov [86]). Less experienced climbers, on the other hand, showed no particular bias towards any part of the route, attempting to reconstruct it in a global manner [38]. Experienced climbers also tended to simulate movements during recall—something the inexperienced climbers never did (also shown in Pezzulo et al. [40]). When asked to verbalize what they were thinking during recall, experienced climbers primarily described usable properties, such as what grasping action or movement could be performed with holds (experiment 2) [38]. In contrast, inexperienced climbers tended to verbalize about the holds' structural features, such their shape or size (experiment 2) [38] (findings supported in Seifert et al. [51] and Pezzulo et al. [40]). Supporting the notion that the ability to perceive actions supported memory of the route properties, Pezzulo et al. [40] showed that inexperienced individuals could match the recall level of more experienced climbers when previewing an easy route that both groups could successfully climb. Furthermore, the experienced group demonstrated a significant reduction in recall performance on a route that was impossible to climb. This outcome suggests that the ability to use the route assisted recall when movement opportunities were perceived, and that new movement opportunities were acquired in relation to experience.

4.2.2 Skill Can Be Predicted Across a Range of Coordination Variables that Support Fluency

Incorporating multiple types of coordination variables into performance analysis may also be an important approach for understanding climbing skill. For example, Sibella et al. [48] described two types of traversal strategies: agility and power. In an individual analysis, a climber who adopted a power strategy showed a higher GIE (less fluency), tended to use fewer than four holds at a time and displayed greater average hip acceleration and variability. According to Sibella et al. [48], this constellation of outcome variables seemed to emerge because the climber had not developed advanced coordination skill. Similarly, Seifert et al. [26]

showed that specific characteristics of acquired coordination patterns support performance fluency (see also Boschker and Bakker [52]). Seifert et al. [26] tested transfer of experienced rock climbers and inexperienced rock climbers when they were climbing in an unfamiliar ice climbing environment. Climbing fluency, defined in terms of continuous vertical displacement, was related to an ability to use a repertoire of inter-limb coordination patterns, such as crossing the limbs, which were unavailable to the inexperienced group. These differences in coordination acquisition supported a positive transfer of performance in terms of minimization of prolonged pauses and an ability to use existing features of the ice wall to achieve anchorage (shown in a lower ratio of ice tool swinging to definitive anchorages) [26].

4.3 Practice Effects in Climbing: Implications for Understanding the Impact of Intervention on the Rate of Learning

A major limitation of expert–novice comparison approaches is the lack of knowledge of how functional adaptations are acquired. However, understanding of issues such as the role of the existing skill level on transfer [26], how or why new coordination modes emerge, or the specific impacts of interventions and pedagogical strategies [52] needs to be approached by observing coordination behaviours over practice and learning timescales.

4.3.1 Exploration and Practice Improve Fluency

A common observation in less experienced climbers concerns their overt exploratory behaviours. Exploratory behaviours have been assessed in terms of touching, but not using, climbing surfaces within a route [26, 51, 95, 96]; qualitative assessment of ‘kinks’ or ‘knots’ in hip trajectories [39]; time spent without movement to devote to a visual search [41]; visual fixations while stationary [50]; and, finally, periods of haptic exploration while in contact with a hold prior to using the hold [44].

Broadly, practice effects indicate that exploratory behaviours reduce with practice [39, 96], while indicators of improved efficiency increase [24, 39, 44, 52, 80, 95]. Boschker and Bakker [52] showed that practising under instruction to use a less advanced coordination mode can still result in improved climbing fluency at the same levels as a more advanced technical action. This finding suggests that practice of the same movement pattern can still improve fluency despite it being less technically advanced. Whether this is true as the route difficulty increases needs to be investigated. Boschker and Bakker [52] also demonstrated that a group of beginners who were shown (and instructed on) how to use an advanced coordination pattern immediately displayed better climbing fluency than groups who were not shown the pattern. However, it is notable that, despite practice, the control group in this study, who were instructed to climb as they liked, never began to use the advanced coordination pattern. This finding suggests that pedagogical intervention plays an important role in assisting individuals to find new skills and can increase the rate of improvement in performance. In this respect, Seifert et al. [96] showed a relationship between exploration of new climbing actions and modification in technique (pinch gripping as opposed to overhand grasping), which appeared to be facilitated by specific properties of the route design. In the study by Seifert et al. [96], holds were designed to be usable with different hand orientations, where advanced actions were more advantageous if used at crux locations. Considering the study by Seifert et al. [96] alongside the findings reported by Boschker and Bakker [52], it may be that, unless constraints in the design of route properties require a modification in coordination (such as reorientated reaching or grasping actions) to improve climbing fluency, new or better coordination of behaviour will not be explored by the learner. Route design, and potentially exploration, appear to be related to the emergence of a more advanced climbing technique.

4.3.2 Existing Skills Increase the Rate of Performance Improvement and May Determine Whether Learning Opportunities Are Available

Cordier et al. [39, 45, 79, 80] provided evidence that the existing skill level also improves the rate of learning under a fixed set of constraints. Cordier et al. [39, 45, 79, 80] showed that an advanced group of climbers reduced entropy to an asymptotic level up to four trials faster than an intermediate group climbing the same route. Exploratory behaviours were related to ‘kinks’ or ‘knots’ in hip trajectories [39], increasing the global level of entropy. One reason why the more experienced group exhibited lower entropy was that the route was within their ability level [54]. Indeed, this may also be one reason why, in extant research, when skill comparisons are made, more experienced climbers do not tend to exhibit overt exploration and display better levels of efficiency, because they are not challenged to find unfamiliar movement solutions due to the relative difficulty of the task [26, 44, 51, 95]. For example, a recent pilot study [86] reporting on a new approach to assess preview behaviour highlighted the impact of scaling route difficulty on adaptive behaviour. In the report by Grushko and Leonov [86], gaze position data of an on-sight route preview were compared between performances on an intermediate route and an advanced route. The climbers (national standard) were also required to lead-climb the routes after preview. While all participants completed the easier route, 48 % fell on the harder route. Interestingly, both fixations and preview time increased on the more difficult route. Furthermore, a qualitative difference in preview strategy was also reported, highlighting how the relative difficulty of a task can substantially alter climbers' tendency to explore a route's properties in skilled individuals.

4.4 Task and Environmental Manipulations in Climbing Research: Implications of Constraint Manipulation from Theoretical and Applied Perspectives

When combined with dynamic coordination measures, constraint manipulation can (a) decipher whether experimental and performance contexts are representative [41, 49]; (b) highlight similarities and differences in behaviours between different training contexts [26, 36, 41, 55, 78]; and (c) show how stability in performance is maintained or destabilized through observing the adapted behaviours [50, 62, 66, 81–83, 92, 93, 95, 99]).

4.4.1 Constraint Manipulation Can Be Used to Affect Exploratory Behaviour in Climbers

Exploration from a learning perspective is an important behaviour because it can allow individuals to find new patterns of coordination and modes of regulating these acquired patterns [30, 107]. Pijpers et al. [66, 92] outlined the importance of distinguishing exploration from other actions in climbing, stating that 'performatory movements are meant to reach a certain goal', while 'exploratory movements are primarily information gathering movements' [66]. Therefore, exploratory behaviours reveal a need to find behavioural opportunities because of a momentary inability to detect any that are presently desirable. However, the current research in climbing pertaining to the exploration/learning relationship is not entirely clear. On the one hand, exploration has been shown to be related to more narrow attention [50, 66, 92], suggesting that exploration is related to a deterioration in performance. On the other hand, it has been shown to decrease with practice as performance concurrently improves, suggesting a functional relationship [95, 96].

Pijpers et al. [66, 92] reported that anxiety (caused by having inexperienced individuals climb at height) can narrow attention [66], reducing how far individuals perceive themselves as capable of reaching [66]. Induced anxiety also led to an increase in exploratory and performatory behaviours [66]. Nieuwenhuys et al. [50] replicated the technique of using height to induce anxiety in inexperienced individuals and considered the impact on coordinating gaze and movement. Fixations were characterized as either performatory (when the fixation occurred during a movement) or exploratory (when the fixation occurred and the climber was stationary). Participants reduced the search rate (the total number of fixations divided into the sum of the fixation durations) and showed a tendency to increase exploratory fixations relative to the number of performatory fixations. Specifically, the ratio of performatory to exploratory fixations went from 6.9 ± 1.38:15 ± 4.88 (low) to 8.2 ± 2.55:23.3 ± 10.22 (high) [increasing the number of exploratory fixations relative to performatory fixations by roughly 1 in the high condition]. Furthermore, climbers also increased performatory actions (low = 21.6 ± 2.91 versus high = 24.5 ± 3.50), suggesting an ongoing coupling of visual–motor behaviours between conditions. However, data on exploratory actions were not reported, and more direct measures are needed to evaluate visual–motor coordination in climbing tasks.

In contrast, exploration can also be interpreted as functional on the basis of how it supports goal achievement throughout practice. In this respect, Seifert et al. [95] observed intermediate performers climbing two separate routes that were graded at the same difficulty level but differed in hand-hold properties. One route consisted entirely of holds either with two graspable edges or with a single graspable edge (20 holds per route). The investigators assessed jerk coefficients of the climbers' hip movements over four trials of practice and showed that only in the double-edged route did the climbers show an initial elevation of jerk, followed by a reduction and asymptote at the same level as the other route (presumably due to the choice at each hold). This pattern also corresponded to the data on the climbers' exploratory actions (touching but not grasping holds), which reduced from 4 at the first trial to 1 at the last trial on the single-edged route, and from 9 to 3 on the double-edged route. These findings suggesting that, through exploration, the experienced climbers determined an efficient path through the route, improving performance.

4.5 Future Research Directions

A number of biases and limitations in the literature favour a variety of novel future directions. A large number of studies were undertaken on an indoor climbing wall; in fact, only four studies could be confirmed as occurring outdoors [24, 42, 51, 108]. This differentiation of conditions clearly has influenced the material properties and specialized equipment that climbers have been tested using, which predominantly involve man-made holds but have included ice [26, 42, 51, 97, 108, 109] and rock [24]. Additionally, research on climbing under top-rope conditions far outweighs studies under lead-rope conditions, where only five studies have involved lead-rope constraints [36, 44, 55, 86]. Additionally, the vast majority of studies have failed to report whether participants were given an opportunity to preview a route before trials (for exceptions, see Sanchez et al. [41], Boschker and Bakker [52], Fryer et al. [58], Grushko and Leonov [86], and Seifert et al. [95]), which has recently been shown to influence climbing behaviours [41], suggesting a bias towards studying movement coordination in isolation from perceptual processes.

Of additional concern is that studies addressing research priorities in coordination acquisition more generally remain sparse and should be addressed as a matter of priority in climbing-specific contexts. They include analysis of processes such as feedback (none could be identified) and transfer of skill (only one study has [indirectly] assessed this [26]); finally, how performance evolves with practice over timescales on which individuals normally develop skill has not been examined. For example, the largest number of practice trials tested has been ten [39, 45, 79, 80], which is notably much less than would be expected of the practice volume involved in acquiring a high level of climbing skill. Furthermore, the effects of intervention have not been considered from a skill acquisition perspective, with only one study involving independent groups during practice [52]. The remainder of the studies have evaluated practice under different conditions [52, 95, 99], hence making it difficult to isolate the mechanisms underpinning improved performance. To address this concern, practice effects using pre- and post-intervention measures of skill are needed and are currently lacking in the literature.

Research developments, however, appear very promising, with current technology suggesting the capacity to address skill across multiple levels of analysis, including eye tracking [50, 86], estimation of the body's motion using automatic worn sensors [87, 90, 95, 108, 110] and instrumented holds for estimating reaction forces [44, 81–83, 99]. Although few studies have adopted an integrated measurement approach, some exceptions could be found. Specifically, a number of studies have combined analysis of movement coordination data with contact forces [43, 92, 94, 111], gaze position data [50] and perceptual self-report [38, 51]. A major future challenge will be to successfully and efficiently integrate these different methods to observe interactions of climbers and surfaces in natural performance environments.

5 Conclusion

Skilled climbing has been broadly characterized as rapidly and fluently transitioning between holds. Elite climbers exhibit a clear advantage in detection and use of climbing opportunities when visually inspecting a route from the ground and when physically moving though a route. However, direct evidence of the coordinated use of visual information has not been reported and should be a priority. Furthermore, perceptual and motor adaptations that improve measures of climbing fluidity, in the spatial and temporal dimensions, are consistently reported in relation to a higher climbing ability level. In addition to this finding, specific hand, limb, postural and inter-wall distancing adaptations have been associated with skill. These two features of skilled climbing have been suggested to bear a relationship, where coordination of actions, such as limb activity, can improve skilled performance (i.e. climbing fluidity). Future research priorities should therefore be placed on developing approaches for understanding the contributions of the coordination of perceptual and motor behaviour to fluidity. Finally, with regard to learning, exploratory behaviour appears to be a potential mechanism supporting new skills development and improvement in performance over time. A hypothesis developed in this review has been that facilitating exploratory behaviour during practice may improve transfer of skill, because it may assist individuals to practise a greater variety of climbing patterns of coordination. Future research should determine if interventions that improve skilled climbing behaviour can be designed by manipulating task and environmental properties on the basis that they induce exploratory activity. With such data, practitioners can be supported in how to utilize the extensive range of constraints available during climbing training to induce exploration of actions that support climbing fluidity relevant to an intended performance context (such as a specific climbing discipline).

Constraints on coordination in climbing, and the effects of practice and skill level, have been considered in relation to preview and climbing tasks. Experienced climbers are able to perceptually simulate how they would climb a route, using information related to opportunities for action. Simulation behaviours are based on multiple modes of information, improve the ability to remember climbing surface features and can be used by experienced climbers during performance, to enhance fluency. Forces applied to hand-holds also reveal a range of behavioural adaptations and are useful for evaluating the effects of modifications in hold properties. Practice effects on performance reveal a number of important characteristics that practitioners should consider when setting up learning interventions. Specifically, practitioners need to be sensitive to the potentially functional nature of exploration. Research priorities should be placed on evaluating the impact of interventions on learning with an emphasis on understanding how new skills are acquired and what pedagogical strategies can improve the transfer of skill.

Compliance with Ethical Standards

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