Body mass center optimization in sport climbing

Pierre LEGRENEUR, Associate Professor

Faculty of Sport Sciences

University of Lyon, France

pierre.legreneur@univ-lyon1.fr

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1 INTRODUCTION

One role of trainers is to plan the training of athletes and orient their teaching toward a balance between the constraints of the sport and the qualities of the individuals. For this purpose, they need objective indicators of performance that are practical to use during training sessions and competitions. For maximal performance in sport climbing, whether on real rock or in competition, the first criterion should be the performance achievement itself, whether that is a successful redpoint or the highest step on the podium. However, this criterion of success, even if it is ultimately the goal of any training plan, is hardly meaningful for the development of the factors of performance.

Climbing consists of displacing the body's center of mass (BMC) from the bottom of the route to a higher point which may be at the top of a cliff or natural boulder or a maximum height in competition. This BMC trajectory is the consequence of the body segments' displacements over time, which I will call the gesticulation[1] of the climber. Consider the importance of the head-neck-trunk system whose mass is about 58% of the whole mass of the climber (Winter, 2009).

[1] About the use of 'gesticulation', many words are used in the literature. In biomechanics, a movement is a displacement of any part of the body (or the body itself); An action is related to an effect. It is used to define au causal relationship, *e.g.* between muscle force development and movement; a locomotion is defined by a displacement of the BMC; gesticulation is the cause of locomotion, *i.e.* the movements of the body segments are actions that induce a locomotion.

The gesticulation itself responds to a need for balance between the characteristics of the support (e.g. the wall), whether natural or artificial, and the motor skills of the climber. In other words, the climber has to realize a [more or less] long temporal sequence of motor actions that responds to musculoskeletal coordination's[2] which are influenced by the following constraints: the nature of the support, the inclination of the support, the quality of the holds, and the spatial distribution of these holds. However, within these constraints, there is potentially an infinite number of BMC trajectories. In addition, each trajectory corresponds to an infinite number of possible inter-articular coordination's. Bernstein (1970) called this indetermination problem the degrees of freedom redundancy. The art of the coach will be to solve this complex problem and to facilitate the climber's ideal trajectory and optimal postures through teaching situations and appropriate instructions. This interaction will help the climber to achieve maximum performance.

The coach is therefore faced with two parameters on which he can work: (*i*) the trajectory of the BMC and (*ii*) the gesticulation required to produce this trajectory. For each parameter, the coach will have to choose an optimal solution (*i.e.* that meets performance objective criteria) among an infinite number of possibilities. The gesticulations required to produce this optimal solution involve a complex relationship between the physical qualities of the climber and the trajectory of the BMC. The solution is therefore multifactorial and results from inter-articular coordination, which is dependent on recruitment of the muscles that cross these joints, which themselves depend on the immediately mobilizable energy, the architectural characteristics of the muscles, and their kinematic parameters such as their lengths and contraction velocities.

In this paper, our purpose is not to focus on gesticulation itself, but on its *prima causa*, *i.e.* the trajectory of the BMC. Indeed, if this trajectory is not optimal, the energy consumed by the climber will be so important that all efforts devoted to gesticulation will ultimately have little effect. Before going further, I will first explore the concept of energy.

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[2] Coordination is defined as a spatiotemporal sequence (where and when) of the different parts of the body for producing a movement or a locomotion. Different heuristic levels of coordination can be considered, i.e. intra-muscular coordination's, inter-muscular coordination's, musculoskeletal coordination's, inter-articular coordination's.

2 ABOUT ENERGY …

Figure 1. *Energy expenditure measurement in climbing using a portable gas analyzer (Metamax3B, Cortex, Germany) (Panackova et al., 2014).*

Antoine Lavoisier, a French scientist that lived at the end of the 18th century, was the author of the following well-known sentence: "Nothing is lost, everything is transformed". This is true in the case of energy. Energy simply transfers, with no gain and no loss. For example, when a climber goes up, he or she uses chemical energy that is transformed by the body into mechanical energy. This mechanical energy exists in two forms: (*i*) kinetic energy, which is proportional to the square of the BMC velocity, and (*ii*) potential energy, which is proportional to the height of the BMC in reference to the ground. These energies are also proportional to the mass of the climber. When the climber falls, he or she loses potential energy that is transformed into kinetic energy, as velocity increases with the height of the fall. At the end of the fall, the energy is absorbed by the climber and the belay chain. Thus, there is no opposition between mechanical and chemical energies, and as a result, one can be evaluate in order to understand the other. In other words, they are two faces of the same phenomenon. In sport, and more especially in climbing, it is very difficult to quantify the energy transfer, or flux, through physiological procedures. Indeed, it would require heavy instrumentation for evaluating oxygen consumption (Bertuzzi *et al.*, 2007, España Romero *et al.*, 2012, Panackova *et al.*, 2014, Watts & Drobsih, 1998, Watts & Ostrowski, 2014) (Figure 1). Moreover, these are indirect measurements as only energy cost indicators, such as VO2, are recorded and not the energy itself. As a result, the only solution for quantifying the energy in ecological conditions (training sessions or competitions) is to characterize the mechanical parameters of individuals. The drawback is that this analysis requires a mathematical description that is difficult to access for the layman.

In concert with chemical and mechanical energy, as well as potential and kinetic energy, this paper will distinguish the following two forms of energy:

- Internal energy is required for the gesticulation of the climber. It concerns the transfer of energy between the musculoskeletal systems and the other elements of the body, ultimately working to create joint displacements and postural purpose (fight against gravity) for the climbing move. Quantifying this energy requires to model the climber in 3D (Figure 2) in order to consider the musculoskeletal parameters.
- External energy depends on the relationship between the body and the environment. This energy is the easiest to quantify as only the knowledge of the BMC position at each instant of the locomotion is needed. An elevation of the BMC induces an increase in potential energy. Any change in BMC velocity will modify kinetic energy. Thus, external energy allows to estimate the whole energy consumption of the climber during gesticulation. It could be a good indicator for trainers to use during training sessions or competition in order to quantify the performance of the athlete. However, note also that a limiting factor of this method is attained when the BMC is motionless, *e.g.* no elevation and zero velocity.

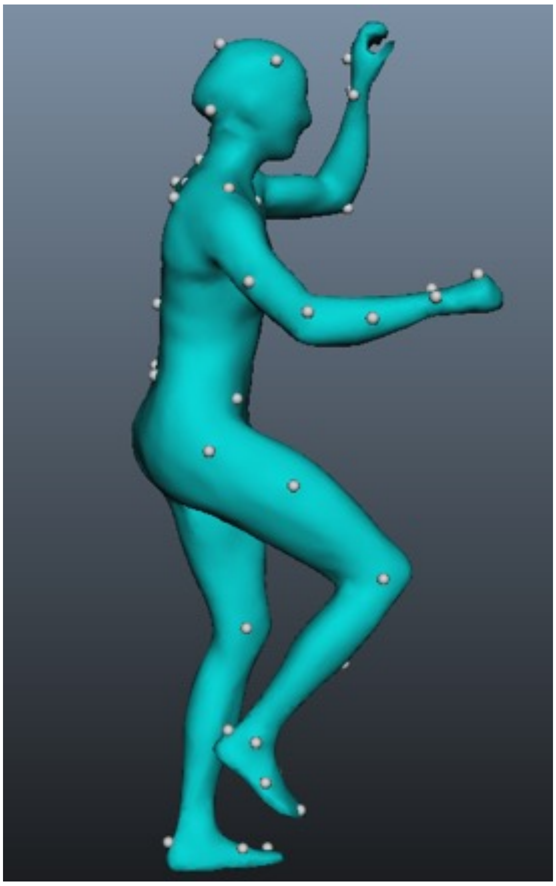

Figure 2. *3D modeling of a climber (Reveret et al., 2018).*

3 BMC PATH IN SPORT CLIMBING

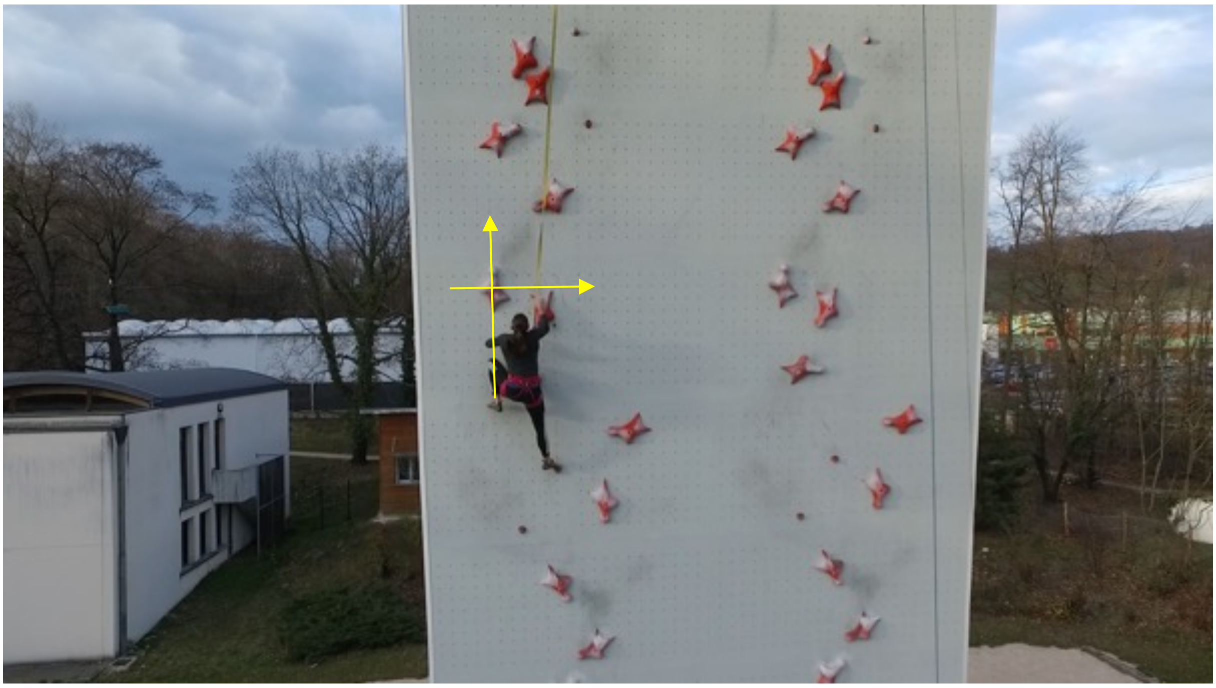

Figure 3. *Acquisition of the gesticulation of a speed climber using a drone (DJI Mavic pro) (Legreneur et al., 2018).*

The BMC is mathematically defined as the centroid of the centers of mass of the different segments of the body. In other words, the BMC 3D location depends on the masses and positions of the body segments (e.g. the head, the trunk, the upper and lower limbs), and thus the body posture on the wall. In standing position, the BMC is located in front of the 3rd lumbar vertebra and can be located near the belly button. However, perfect standing position is extremely rare, as the slightest movement of any segment will displace the BMC. To evaluate the path of the center of gravity, the acquisition of the movement is needed. I do this by filming the climber during his or her performance (Figure 3). The film is then digitalized to model the locomotion of the climber and calculate the BMC path (Figure 4).

This path does not make sense in itself. So, coaches need objective clues to make this path meaningful. The climber and mountaineer Patrick Cordier (1946-1996) was the first to propose such clues. In 1995, he defended his thesis in neuroscience on "Static and dynamic motor learning: analysis of climbing trajectories" (Cordier *et al.*, 1993, 1994a, 1994b, 1996). Ten years later, this research was continued by Sibella *et al.* (2007) who generalized the results in 3D, and Watts *et al.* (2016), who compared different climbing situations.
Using an ecological approach to climbing, Cordier introduced the concept of entropy to characterize the performance of a climber in relation to the BMC path. How is defined entropy? Entropy is a thermodynamic concept created in 1865 which means (in Greek) transformation. In physics, entropy describes the degree of disorganization of a system, and in the specific case of climbing, the degree of disorganization or complexity of the BMC path. In climbing, a minimum degree of entropy (or complexity) is a straight line from the start to the finish of the climb. The energy expenditure could then be characterized as minimal. Any deviation of the center of gravity from this line will induce an increase in the distance traveled, and therefore an increase in energy expenditure. However, in climbing, the trajectories are rarely linear and constrained by the topology of the holds and the location of the anchors. Thus, each path will have its own minimal entropy index. To calculate this index, fractal mathematics are used (Mendès France 1981, 1983, 1991). Without going into detail, this index will depend on the length of the trajectory of the BMC (in yellow in Figure 4) as well as the perimeter of the convex hull of the trajectory (in white in Figure 4).

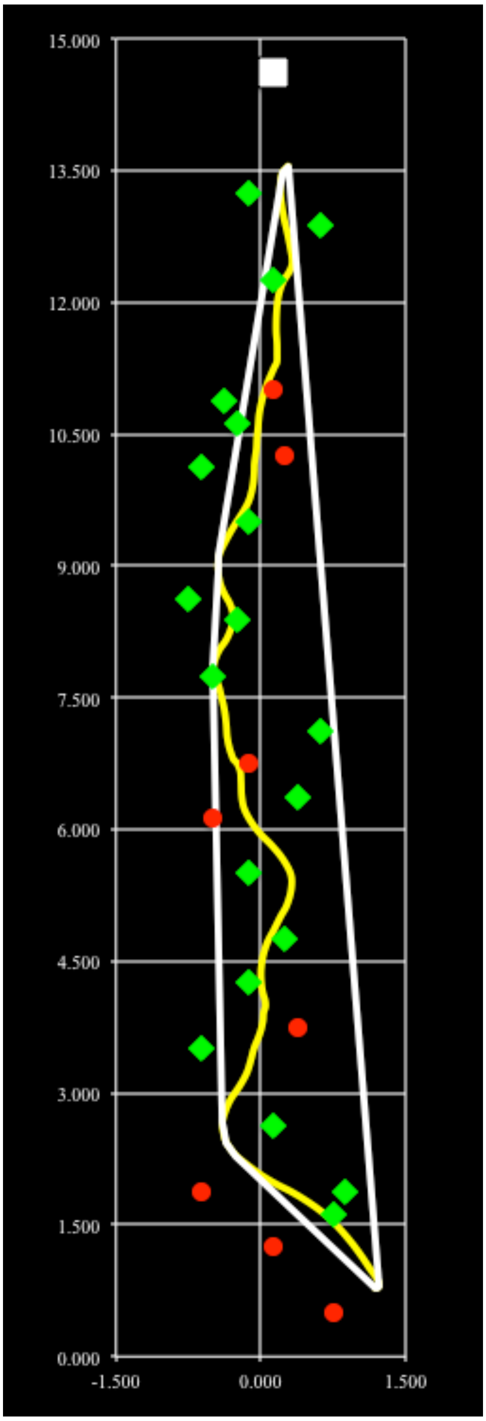

Figure 4. *BMC path (yellow) and convex hull (white) in speed climbing. Red and green dots indicate the feet and hands' holds (respectively) of the official route (Legreneur et al., 2018).*

In addition to the entropy index – which is, as later explained in the text, a clue to performance – viewing the kinematics of the center of gravity allows to consider its energy dimension (Figure 5). This dimension is important because it gives information about the climber's technique and his or her ability to conserve energy, thus optimizing performance. Kinetic and potential energy indicate different aspects of performance. The potential energy tells us about the climber's height variation. Even though potential energy may be less important to lead climbing and bouldering, it is essential in speed: the more the curve of the line is smoothed, the more the climber will be able to propel him or herself upward with a minimum of deviation from the optimal path. The kinetic energy, on the other hand, accounts for the speed variation of the climber. Ideally, in speed climbing, it will be optimal to keep the BMC velocity constant (no acceleration or deceleration), thus experiencing no variation in kinetic energy. Here, the variations of these energies may be considered indicators of progress margins for the athlete.

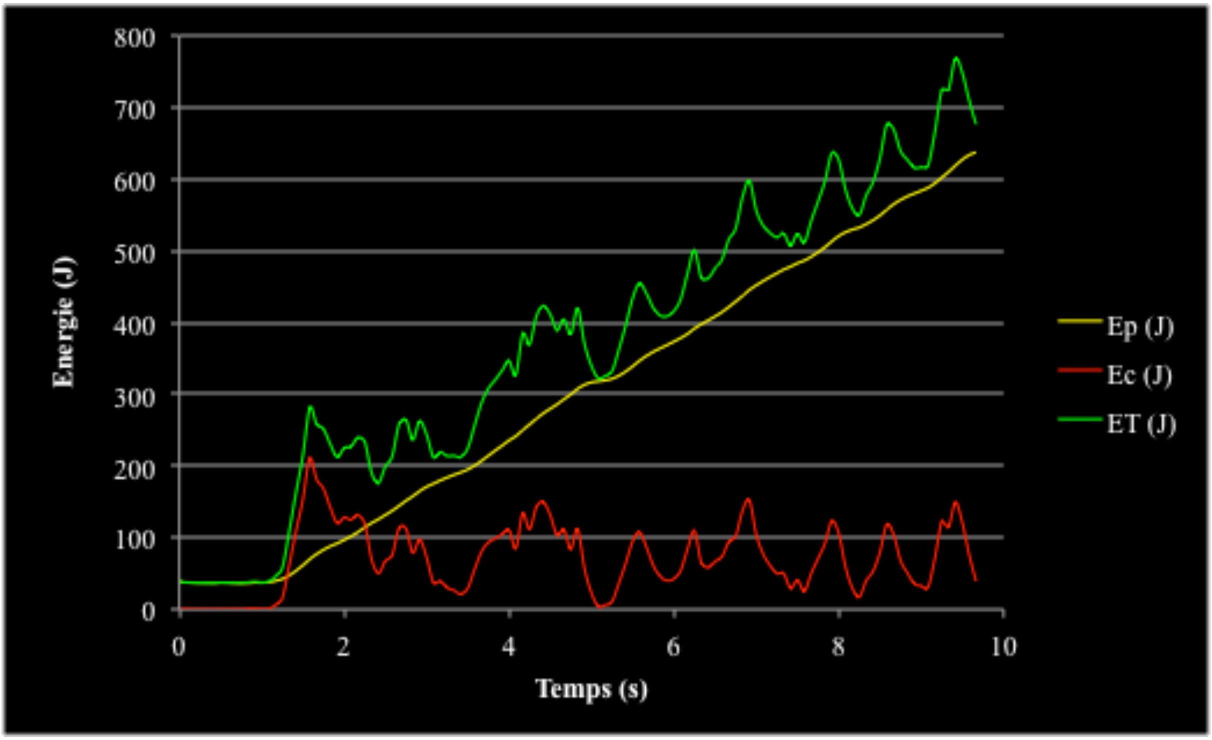

Figure 5. *Potential (yellow), kinetic (red) and mechanical energies (green)* vs. *time in the official speed route (Legreneur et al. 2018).*

4 ENTROPY AND PERFORMANCE IN SPORT CLIMBING

4.1 Climber typology and entropy

To succeed on a route, there is always an abundance of solutions depending on the physical and technical qualities of the climber. Thus, it is possible to distinguish two strategies: agility and force (Sibella *et al.*, 2007). According to Sibella, the agility strategy requires less speed and less power for the movement to be successfully completed. The force strategy is based on power and requires more speed and more force for the movement to be successfully completed. Sibella *et al.* (2007) proposed that "the first strategy could be the more effective, because it requires less power, more fluency and more control of the equilibrium". From my point of view, it is better to replace speed with acceleration in these definitions. Indeed, according to Newton's second law, force is directly proportional to the mass and the acceleration of the climber. On the other hand, you can climb with a high velocity but a low acceleration, without producing high force levels. So, I propose the following definitions:

- Agility dominant climbing is based on low acceleration level and force, with a predominance of equilibrium control;
- Force dominant climbing is based on high acceleration level and force.

So, considering an agility dominant climber and a force dominant climber with the same absolute maximal strength, it is obvious that the first one (agility) will potentially have a longer duration of BMC displacement (and not necessarily longer BMC trajectories) along the optimal path than the second one (force). As a result, the goal of the coach should be to ensure climbers pursue agility dominance for the following reasons:

- In lead, the mean climbing duration, without relative rest positions, is about 3min 30 sec in international events (personal data). As a result, the climber has a maximum time of 3 min 30 sec to achieve a maximum number of movements. Let's compare agility dominant with force dominant climbers which displace with the same BMC velocity. If the climber is force dominant, this gesticulation duration will be reduced and he or she will enter into a vicious training circle: to increase this duration he or she will have to work on his or her physical qualities, *i.e.* increase strength and / or resistance, and therefore increase the tendency to be force dominant. In agility dominant climber, the goal is to climb precisely and rapidly along the optimal BMC path.
- In bouldering, the climber with agility dominance will be able to use a greater percentage of maximum force in holding power or propulsion. Posture will be solved by displacing the BMC near the wall and / or the vertical projection of the BMC into the support polygon. Thus, less force will be used for postural function than in force dominant climbers.
- In speed, the agility dominant climber will have less speed variation across the route and will be able to play on the conservation of energy to accelerate from the beginning to the end of the track.

Entropy is indicative of these typologies (Sibella et al., 2007). Thus, the entropy is always greater in force dominant climbers. This means that they do not optimize their BMC paths and therefore travel a greater distance than the climbers with agility dominance. Consequently, their energy consumption will increase and their performance will fall.

In summary, an agility dominant climber achieves a route with less movement than a force dominant climber. This means that at equivalent strength levels:

- he or she will go higher on the route;
- he or she can use higher percentages of maximal force in the movements since they will perform fewer muscular contractions than the force dominant climber;
- he or she will present low speed variations and consequently will expend less energy than a force dominant climber;
- he or she can paradoxically use more strength to grip holds in a route than a force dominant climber, as their strength is not used for postural function.

Performance is therefore a compromise between force and agility that is best used to achieve maximum performance. This compromise differs according to the specialty (bouldering, lead or speed). Moreover, in the context of the Olympic combine, where climbers will perform the three events, it seems absolutely necessary to place a special emphasis on these technical aspects.

4.2 Expertise and entropy

Entropy is also an indicator of climbing learning. Thus, Cordier et al. (1994) demonstrated that the climber's entropy index decreased with the repetition of a route to a minimum plateau that is specific to each climber based on its physical and technical qualities (Figure 5).

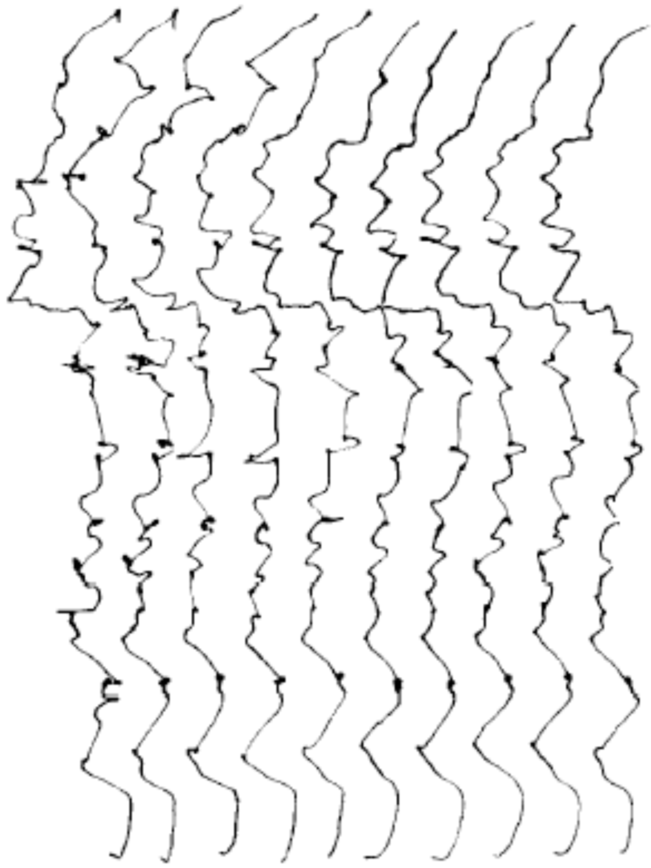

Figure 6. *Image of learning process: family of 10 successive trajectories reaching a stable state (from Cordier et al., 1994a)*

In addition, entropy depends on the level of expertise (Figure 6). Thus, the higher the level of expertise, the lower the entropy. Motor learning also acts differentially with the level of expertise. Indeed, the experts stabilize the entropy faster during the tests than beginners.

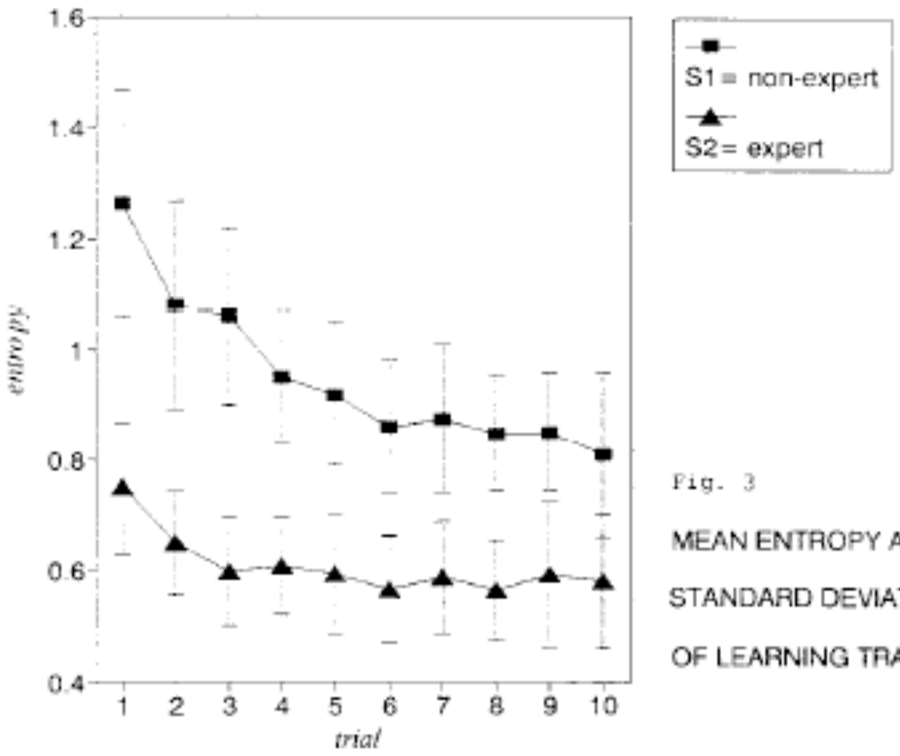

Fig. 3

MEAN ENTROPY AND STANDARD DEVIATION OF LEARNING TRAJECTORIES

Figure 7. *Evolution of entropy with route repetition in expert and non-expert climbers (from Cordier et al., 1994a)*

These results suggest that successfully completing a route during training should not be the only goal, as success is not the same as locomotion optimization from an energetical point of view. If training is the main avenue to develop physical, technical and tactico-technical abilities, and optimize performance, then coaches should consider prioritizing the success of the route with a minimal energetic expenditure. Therefore, even if the path has been successful, it is necessary to repeat it until the most economical gesticulation is found. The athlete will therefore have to implement new locomotor strategies to reach this economy. The coach can help with pre-fatigue[3] or use additional loads (at most 10% of body weight).

[3] I call "pre-fatigue" the action of fatiguing certain muscles or all muscle groups before performing the main training exercise. The purpose is to induce an optimal displacement of the BMC since the climber will not have enough strength to maintain equilibrium with his or her muscular force.

5 CONCLUSION

In conclusion, the climber's BMC path, as quantified by its entropy and mechanical energy, is a reliable indicator of climbing performance. This indicator makes it possible to discriminate the level of expertise of climbers, to evaluate motor learning, and to distinguish (for the same level of performance) force and agility dominant climbers. At a time when physical indicators are becoming more important for interpreting performance, it seems necessary to remember that technique and style play a key role in climbing performance. In other words, selecting climbers on the sole criterion of physical qualities is a heresy in a sport where these qualities are at the service of the technique and not the opposite.

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