Introduction

Research interest in rock climbing has increased significantly over the last few years. In order to climb vertical surfaces, the hands are used as the primary effectors. This means that climbers have to be able to generate and/or sustain repetitively large force at their fingertips [15,16]. As a result, the sport of rock climbing has its own spectrum of injuries [11]. Previous reports indicate that three quarters of elite and recreational rock climbers suffer from injuries of the hand [14], and that almost half of all injuries in rock climbing are caused by hand injuries [4,8]. Acute and chronic overuse injuries involve typically ligament or tendon strain in the finger flexors [15], as well as pulley sprains or ruptures in certain cases [11]; note that this brief overview does not take into account more critical injuries caused by a fall.

From a mechanical point of view, maintaining contact with the hold requires minimal grip forces (normal to the contact surfaces) to prevent slipping. Earlier experiments have shown that when an object is hand-held, grip force is substantially larger than the smallest force needed to prevent slipping from the object (\[6,12,25\]; for a review see [9]). Typically, the difference between the minimal force and the employed grip force is defined as the safety margin [25]. Expressed in percent of the minimal grip force, the safety margin can reach 150% or more [6,12]. Because ergonomic studies have often pointed out the causal relationship between biomechanical stress during forceful work and the development of musculoskeletal disorder in the hands [1,2,18], we reasoned that employing repeatedly unnecessary high grip force in rock climbing is likely to increase the risk of hand injuries. To further explore this possibility, and because the consequences of a slip can be harmful in this activity, we investigated how the grip force safety margin was regulated in expert rock climbers.

What predictions can be formulated with respect to the grip force safety margin in rock climbers? On the one hand, because slips are quite dangerous in this activity, it is reasonable to expect that rock climbers are incited to employ high safety margins. On the other hand, experts in rock climbing are also encouraged to use low safety margins because excessive grip force is likely to lead to hand injuries.
increase the risk of muscle fatigue, thereby compromising their ability to repeat or sustain handgrip exercises [24]. In order to separate between these two possibilities, we have measured the grip force safety margin of expert climbers during a simple task, that is holding an object between the thumb and the index finger. Because the need for optimizing grip force is likely to increase with the weight of the object, and the duration of the grasp, those factors have been manipulated in the present experiment. At last, to better interpret the performance of the rock climbers, it was compared to the performance of athletes practicing sports that require minimal manual skills.

Material and Methods

Participants
Two groups of five healthy males took part as subjects in the experiment. The first group was composed of proficient climbers. Their level ranged from regional (French 7A) to national level (French 8A). All of them had at least four years of experience in climbing and scheduled typically two or three training sessions per week. Their mean age, body height and mass were respectively, 21.8 ± 3.4 yr, 1.75 ± 0.06 m, 66.2 ± 6.2 kg. The second group was composed of athletes practicing sports in which manual dexterity and hand strength was not determinant (they were either runners, cyclists, or soccer players). Their mean age, body height and mass were respectively, 21.8 ± 1.1 yr, 1.78 ± 0.06 m, 72.2 ± 6.2 kg. All subjects were right-handed according to their preferential use of the right hand during writing and eating. The subjects had no previous history of neuropathies or trauma to the upper extremities. All the subjects gave informed consent according to the procedures approved by the Mediterranean University.

Apparatus
Two unidirectional sensors were used for grip force measurement. The first sensor (ELPM-T1 M-25 N, Entran, Paris, France, ± 25 N range) was used to measure grip force during holding tasks, and the second sensor (ELPM-T1 M-125 N, Entran, ± 125 N range) was used to measure grip force during maximal voluntary contraction. Each sensor measured only the normal force component (i.e., force perpendicular to the sensor’s surface). Both sides of each transducer were covered with sandpaper (80 grain/cm²). The distance between the contact surfaces was 2 cm. Grasping felt comfortable for all the subjects. One of the force sensors (ELPM-T1 M-25 N) was equipped with an inextensible string onto which different loads could be suspended (see Fig. 1). In some of the trials, the suspended load was further equipped with an accelerometer (EGAS-FS-5, Entran, ± 5 g range) that allowed the vertical acceleration of the object during voluntary load release to be monitored (see later in the method). The output of the sensors was sent to a multichannel signal conditioner (MSC12, Entran). Then a 16-bit analog-to-digital converter (PCI-MIO-16XE50, National Instrument, Austin, TX, USA) was used to digitize the analog output at the sampling frequency of 100 Hz. The accuracy of the two load cells was respectively 0.02 N and 0.1 N.

Protocol
Each subject washed his hands prior to the experiment. During testing, the subject was seated on a chair facing the testing table with his upper arms at approximately 45° of abduction in the frontal plane and 45° of flexion in the sagittal plane, the elbows of flexion, and the wrists in a neutral position. As shown in Fig. 1, the testing table supported the forearms and wrists, but a small fraction of the hands was lying over the edge of the table. The positions of the hands were symmetrical with respect to the body midline. The distance separating both hands was about 20 cm. Using their right or left hand, subject grasped the force sensor between the thumb and index finger (precision, or “pincer” in rock climbing). We explicitly asked the subject to avoid any hyperextension of the phalanges. The three remaining fingers were flexed. When the subject was ready, the experimenter progressively released the suspended load. Then, within the next few seconds, data acquisition was performed for a variable duration (see further in text). The task of the subject was to grasp the force sensor, and prevent the suspended load from slipping. They were neither given suggestions for useful strategies nor they were given instructions regarding suitable normal forces [13]. Across trials, several independent variables were manipulated. First, depending on the trial, the suspended weight could be either light or heavy. Given that rock climbers are known to possess superior pincer strength (about 31% based on [7]), different loads were suspended depending on the group of subjects. For the control subjects, the light and heavy loads were respectively 0.15 and 1.5 kg, whereas they were 0.2 and 2 kg for the climbers. The rationale was that the holding task should be of similar difficulty for the climbers and the non-climbers with regard to the maximal grip force of each group. Second, the duration of the holding task was also manipulated. One duration was short (6 s), and the other long (90 s). Before each trial, subjects were informed about the magnitude of the load, and the duration of the task. Third, the holding task was performed either with the right or the left hand so as to minimize the effect of fatigue within a hand (see further in the paragraph). Overall, subjects went through 8 experimental conditions (2 hands × 2 loads × 2 durations). Each subject performed 3 blocks of trials. Each block consisted of a single trial in each experimental condition. Thus, each subject performed a total of 24 trials. Within each block, the order of the trials was randomized. However, to minimize the effect of fatigue, several constraints were imposed on the experimental design: 1) after each trial, subjects switched from one


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hand to the other, and 2) if the last trial of a given block was the most challenging condition (heavy load/long duration), the next block did not start by a similar trial from the same hand.

In addition to the main experimental conditions described above, subjects performed two types of control trials. In the first type, they were asked to release their grasp slowly until the object slipped. The goal of those trials was to evaluate the minimal grip force needed to hold the load (allowing to estimate the safety margin in the earlier trials). Each subject performed 3 trials with the light load, and 3 trials with the heavy load. The right and left hand were tested separately. Because those trials could possibly help the subjects in optimizing their grip force, those trials were performed at the end of the experiment. In the second type of control trials, subjects were asked to exert maximal voluntary contraction (MVC) for about five seconds. The first goal of those trials was to compare hand strength of climbers and non-climbers. A subsidiary goal was to monitor possible effects of fatigue throughout the experiment. To achieve those goals, each subject performed 3 MVC trials with each hand before initiating the first block, as well as after completing each block. A detailed comparison between the first and the last block showed a reduction in MVC by 8 N (73.8 versus 65.8 N, p < 0.01). No significant difference was found between groups in terms of relative muscular involvement.

Data analysis

Data analysis focused on the relative safety margin (RSM) of grip force (for an example see [10]). RSM was calculated over the first 6 seconds of each trial. This index was computed as follows: \( \text{RSM} = 100 \times \left( \frac{\text{Gf} - \text{Gmin}}{\text{Gmin}} \right) \), with Gf as the average grip force during the first 6 seconds, and Gmin as the minimal grip force to prevent slipping from the object. The value of Gmin was taken at the initiation of slipping from the object during the trials in which subjects were asked to slowly release their grasp. This moment was determined with respect to the first time derivative of the accelerometer signal (see [6]). A RSM of 100% means that grip force is as big as the minimal value, and a RSM of 0% means that grip force is equal to the minimal value. For each subject, and for each experimental condition, RSM values were averaged across the three blocks.

To better characterize the holding task in terms of relative muscular involvement, for each trial, Gf was further expressed as a fraction of each participant’s MVC (i.e., MVC measured at the beginning of each block). This index was called RGf (relative grip force). Next, to provide more insight about the contact at the object-finger interface, an individual estimate of the friction coefficient (µ) was obtained by dividing the load of the object by Gmin (see [6]). This analysis revealed that skin slipperiness was comparable in climbers (µ = 1.06 ± 0.21) and non-climbers (µ = 0.99 ± 0.21). This means that if both groups had held similar loads, Gmin would have been identical across groups.

Statistical analysis

Repeated measure ANOVAS were used as the main tool for statistical analysis. For MVC values, one-way ANOVA were performed with GROUP (climbers/non-climbers) as between factor. For RSM values, three-way ANOVAS were performed with GROUP, plus LOAD (light/heavy) and DURATION (short/long) as within group factors. For the sake of simplicity, the HAND factor (right/left) was excluded from the ANOVA because it did not lead to any significant difference in terms of RSM values (F(1,8) = 0.04, p > 0.05). A two-way ANOVA (GROUP by LOAD) was also performed for RGf values. For all statistical purposes, the threshold of significance of 0.05 was kept constant.

Results

One-way ANOVA of MVC values showed a main effect of GROUP such that climbers had larger MVC than non-climbers (+23%, 75.7 ± 11.1 N versus 60.6 ± 9.1 N, F(1,8) = 5.57, p < 0.05). One of the non-climbers had actually a MVC comparable to climbers (72 N), but excluding this participant from the non-climbing group did not change the meaning of the subsequent statistical results. Concerning the relative grip force, two-way ANOVA showed a main effect of LOAD (F(1,8) = 269, p < 0.001) consistent with the view that RGfs were greater for heavy loads as compared to light loads (44.2 versus 4.5% MVC). However, there was no main effect of GROUP (F(1,8) = 0.13, p > 0.05), nor GROUP by LOAD interaction (F(1,8) = 0.12, p > 0.05), thereby suggesting very little differences between groups in terms of relative muscular involvement.

Three-way ANOVA of RSM values showed no main effect of GROUP (F(1,8) = 2.41, p > 0.05). However, there was a marginal GROUP × LOAD interaction (F(1,8) = 4.56, p = 0.06; see Fig. 2a). Post-hoc Newman-Keuls tests showed that both groups had similar RMSs for the heavy load (148 versus 155%; p > 0.05), but for the light load, climbers had lower RMSs as compared to non-climbers (232 versus 386%; p < 0.05). The ANOVA also revealed a main effect of LOAD (F(1,8) = 18.2, p < 0.01) as well as a main effect of DURATION (F(1,8) = 5.91, p < 0.05). The effect of LOAD was due to the fact that RMSs were considerably larger for light loads as compared to heavy loads (309 versus 151%). Concerning the effect of DURATION, we observed that subjects had a larger

![Fig. 2a and b](image-url)
Discussion

Let us start with a very basic consideration. The present study is consistent with other studies showing that experts in rock climbing have greater hand strength as compared to non-climbers [5, 7, 14, 19] (however see also [22, 23]). In some studies, differences between climbers and non-climbers are not particularly high, but when handgrip force is expressed relative to body mass, as a strength-to-mass ratio, scores for climbers become significantly greater [22, 23]. The magnitude of this difference in our “pincer” task is rather close from what has been reported by Grant et al. ([7]; 23 versus 31%). The slight difference across studies may originate from the fact that in the present experiment, the body mass of the climbers was slightly inferior to the body mass of the non-climbers (66 versus 72 kg), whereas it seemed to be the other way around in the study of Grant et al. ([7]; 75 versus 71 kg). No matter the origin of this slight discrepancy across studies, the fact that climbers were asked to hold objects heavier than non-climbers contributed to level off their superior muscle strength. Interestingly, results showed that this procedure led to similar muscular involvement in terms of maximal handgrip performance (see the analysis of RGf). Overall, thanks to weight adjustments, handgrip force of climbers and non-climbers were presumably challenged in a similar way during the present experiment.

Let us now come back to the original goal of this study, that is investigating how grip force safety margin is regulated in rock climbers during holding an object. The main findings provided by this study are the following: 1) climbers and non-climbers had similar RSM (except when the task imposed to carry a light load), 2) both groups of subjects exhibited a smaller RSM when the load of the object was increased, and 3) both groups used higher RSMs when they planned to hold the object for an extended period of time. We are going to discuss now the implications of those results, especially with respect to hand injury.

Presently, earlier reports have shown that rock climbers are both stronger and more endurant than non-climbers [5, 7, 14, 19], but little is known about their grip force efficiency. If avoiding unnecessary force exertion is considered as a sign of grip force efficiency, then the present study showed that climbers were not more efficient than non-climbers, except when holding very light weights (see Fig. 2a). What are the consequences of this observation in terms of possible hand injuries? Because the risk of hand injuries is very minimal when handling light loads, we conclude that the way climbers and non-climbers adjust their grip force to heavy loads makes them equally prone to hand injuries. However, it is fair to admit that climbing and holding an object are not exactly the same tasks. First, during climbing, the fingers provide support to the body, and the resulting load can be certainly larger than the 2 kg provided in our task. Second, the shoulder, elbow, and wrist are largely involved during climbing [3], whereas they were poorly involved in our task (since forearm and hand were supported). At last, the consequences of a slip are less harmful in our task than during real climbing. Further investigations are encouraged to determine whether similar conclusions would be obtained in the context of a task much closer to the activity of climbing. Based on preliminary data [17], Rougier suggests that climbers could behave differently on a climbing wall, however grip force safety margin was not explicitly recorded during this study.

The fact that all subjects decreased their RSM when switching from a light to heavy object is consistent with one of our earlier studies in which subjects were asked to hold successively a 0.3 and a 1.1 kg object [6]. Indeed, RSMs were respectively 184% and 105% for the light and heavy object. Why would subjects use a lower safety margin for heavy loads as compared to light loads? A parsimonious explanation would be that grip force optimization is more encouraged when the magnitude of the load increases. Let us compare the relative grip force (RGf) that would have been observed if our subjects held the object with a high (300%) or a low (100%) RSM. If subjects held the light load, a change in RGf from 2 to 4% would have led to minimal consequences for the performer; under 10% MVC, energy expenditure is minimal, and endurance time is virtually unlimited [10]. By contrast, if subjects held the heavy load, a similar change in RSM would have radically changed the level of muscle contraction associated with the task, since, in that case, RGf jumps from 35 to 70% MVC. For illustration, West et al. [24] reported that the maximal endurance time at 30% MVC is 364 s, but decreased to 139 s at 70% MVC. Whatever the underlying mechanism responsible for this reduction in RSM at larger loads, this mechanism contributes to the prevention of injuries when the human’s hand needs to support heavy loads. However, it remains to clarify why humans do not eventually use a lower RSM, since the muscle cost associated with an RSM of 150% is already significant. A very surprising phenomenon was that both climbers and non-climbers increased their grip force when they were asked to hold the object for an extended period of time (as compared to a short period). On average, RSM increased by a factor 1.15. This phenomenon was rather robust since it was observed for both types of loads (Light = 1.13, Heavy = 1.17; see Fig. 2b). With respect to the goal of the task, this behavior does not seem very appropriate (especially for the heavy load). Indeed, subjects are more likely to face muscular fatigue, thereby compromising their ability to hold the object for an extended period [24]. Why did we observe an increase in RSM if it is detrimental to the performance? Recently, using computer mouse tasks, it has been shown that, with mental pressure, grip- and click-forces increased by 51% and 40%, respectively [20]. Along this line, we suggest that the effect seen in our study could reflect some kind of cognitive stress. When subjects were asked to hold the heavy load for 90 s, some of them clearly expressed suspicion about the fact that they could actually complete the trial. Although this scheme provides a satisfying explanation for the heavy load, it remains unclear why this effect was also observed for the light load (a non-challenging task). Further studies should investigate whether providing explicit feedback on safety margin could help subjects in repressing this kind of behavior, and thereby extend their prehensile performances in terms of endurance.

Overall, we conclude that rock climbers, as compared to non-climbers, are not characterized by key changes in the way they regulate their grip force safety margin. With respect to the risk
of hand injury, on the other hand, the progressive reduction in safety margin at larger loads helps minimizing this risk. But on the other hand, the fact that grip force is still so crudely optimized at a large load (RSM = 150%), as well as its additional elevation when planning to sustain a hold, does promote the risk of hand injury in climbers. Although interesting to the sport climbing community, those results could also have implications for the ergonomic community, especially if one takes into account that the risk of developing work-related musculoskeletal disorders is high when hand and wrist forces are repeatedly above 20% MVC [2].

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References