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„Patterns of joint coordination and muscles activation during a fatiguing finger hanging task in climbing“

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Abstract

The aim of this study was to assess and describe climbers' upper body muscle activation and joint coordination strategies during maximal hangs under non-fatigued and fatigued conditions. Therefore, 13 healthy climbers (26 ±5.2 years; 178 ±5.8 cm height; 72 ±6.9 kg and 22 ±3.3 IRCRA) performed one maximal finger hanging on a 20 mm ledge in a half-crimp finger position. Upper body muscle activation (sEMG) and kinematics were recorded. The root mean square (RMS) and median frequency (MF) of the sEMG signal were calculated, and joint coordination was assessed through vector coding analysis. Results showed an increase of the muscle RMS and a decrease in the MF. The only exception was the MF of the *trapezius transversus* ($t(12) = -4.63$, $p<0.001$) which increased. The MF of the *pectoralis major* ($z = -0.75$, $p = 0.4$) remained the same. Noteworthy is the *flexor digitorum superficialis* ($z = -1.49$, $p = 0.14$), which did not significantly change under fatigue. The study showed that fatigue demands a specific coordination pattern of the upper limb joints accompanied by muscle activity, especially in the sagittal plane, where wrist extension was dominant in the unfatigued state, whereas in the fatigued state, upper limbs getting more involved (e.g. coupling 1: unfatigued: M = 183.78, SD = ±23.61, fatigued: M = 144.77, SD = ±28.46; $t(12) = 4.366$, $p<0.001$). These results can be seen as anticipatory postural adjustments, which minimize the expected balance perturbation caused by the narrow basis of support and contribute to the hanging efficiency.

Keywords: muscle fatigue, maximal hangs, climbers, sEMG, kinematics, vector coding

Zusammenfassung

Ziel dieser Studie war es, die Aktivierung der Oberkörpermuskulatur und die Gelenkskoordinationstrategien von Kletterern beim maximalen Hängen unter nicht ermüdeten und ermüdeten Bedingungen zu untersuchen und zu beschreiben. Zu diesem Zweck führten 13 gesunde Kletterer (26 ±5,2 Jahre; 178 ±5,8 cm Körpergröße; 72 ±6,9 kg und 22 ±3,3 IRCRA) ein maximales Hängen an einer 20 mm tiefen Leiste in einer halb gekrümmten Fingerposition durch. Die Muskelaktivierung und Kinematik des Oberkörpers (sEMG) wurden aufgezeichnet. Der quadratische Mittelwert (RMS) und die mittlere Frequenz (MF) des sEMG-Signals wurden berechnet. Weiters wurde die Gelenkkoordination durch eine Vektorcodierungsanalyse bewertet. Die Ergebnisse zeigten eine Zunahme des Muskel-RMS und eine Abnahme der MF. Die einzige Ausnahme war die MF des *Trapezius transversus* ($t(12) = -4{,}63$, $p<0{,}001$), welche anstieg. Die MF des *Pectoralis major* ($z = -0{,}75$, $p = 0{,}4$) blieb gleich. Beachtenswert ist der *Flexor digitorum superficialis* ($z = -1{,}49$, $p = 0{,}14$), welcher sich unter Ermüdung nicht signifikant verändert hat. Die Studie zeigte, dass die Ermüdung ein spezifisches Koordinationsmuster der Gelenke der oberen Gliedmaßen erfordert, welches von einer Muskelaktivität begleitet wird, insbesondere in der Sagittalebene, in der im unermüdeten Zustand die Handgelenksextension dominiert, während im ermüdeten Zustand die oberen Gliedmaßen stärker involviert werden (z. B. Kopplung 1: unermüdet: $M = 183{,}78$, $SD = \pm 23{,}61$, ermüdet: $M = 144{,}77$, $SD = \pm 28{,}46$; $t(12) = 4{,}366$, $p<0{,}001$). Diese Ergebnisse können als antizipatorische Haltungsanpassungen angesehen werden, welche die zu erwartende Gleichgewichtsstörung, die durch die schmale Basis der Unterstützung verursacht wird, minimieren und zur Effizienz des Hängens beitragen sollten.

Schlüsselwörter: Muskelermüdung, maximales Hängen, Kletterer, sEMG, Kinematik, Vektorcodierung

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1. Introduction

Climbing is a vertical practice performed in a range of different environments, which allows for a diversity of behaviors and permutation of such manners. Although such a feature makes it challenging to categorize this activity, two main types of climbing can be attained as the most popular ones practiced as a physical activity and in competition, especially for the purpose of the present thesis: sport climbing and bouldering. Sport climbing is characterized as a recreational and leisure activity in addition to a training activity for mountaineers (Watts 2004). Sport climbing is characterized by specific belay techniques such as the use of flexible and fixed anchors and the use of rope protection. This type of climbing allowed climbers to explore more challenging terrains and focus on the movement requirements, which were both mental and technical. For a typical sport climbing route in competition, one would spend between 2 and 7 min to ascend (Watts 2004). On the contrary bouldering is climbing at lower heights with mattress floor protection (Lutter, Tischer, and Schöffl 2021), whereas sport climbing is performed on walls (>10m) (Stien et al. 2019). A study conclusion shows that boulder climbers are stronger and more explosive compared to sport climbers, which is reasonable when looking at the new generation of boulder climbers who have to perform in a more acrobatic way than sport climbers used to climb. However, there was no observation of any differences between the two groups in finger flexor endurance (Stien et al. 2019). Based on easier standardization and comparison reasons, this study will only concentrate on topics related to sport climbing.

However, independently on the type of climbing, climbers mostly experience isometric positions to recover from complex movements in the route or before initiating the next movement (Saul et al. 2019), so there is an intermittent nature to the physiological demands in climbing (Ozimek et al. 2017). Furthermore, climbers spend around 37% of their time during an ascent in a static support position (Watts 2004). Such characteristics help to define that the primary energy systems demanded in climbing are aerobic and anaerobic alactic, regardless of training status or skill level (Bertuzzi et al. 2007). Additionally, demands such as upper limb muscle strength and capability of resisting fatigue, especially for the finger flexors, are widely acknowledged as determinants of climbing performance (Ozimek et al. 2017).

Fatigue affects the body's motor behavior and task performance. Local exercises (involving a particular muscle group) trigger compensatory postural strategies to counteract the disturbance of postural control (Paillard 2012). In fact, muscle fatigue is responsible for redistributing the contribution of active muscles and reorganizing the coordination of the joints involved in the task (Yiou et al. 2009). Finger hangings are frequently used to develop neuromuscular and local metabolic capabilities of the finger flexors in climbers, and fatiguing protocols are often used in assessments and training (López-Rivera and González-Badillo 2019). Investigating the principles of the relationship between finger flexors muscles and the postural control of the suspended body during fatiguing hangings would allow for a better understanding of potential risks resulting from this process, thus enhancing sports training and rehabilitation reach. Therefore, the present thesis aims to analyze upper body kinematics coordination and muscle activation during fatiguing hangings in healthy climbers.

This thesis will first give an overview of associated topics such as body actions involved in climbing, kinesiology of the hands and fingers, physical and physiological demands, and the determinants of success in this sport. Further chapters will give a literature overview on muscle fatigue and body coordination. Afterwards, the research question of the actual thesis will be presented, as well as its aims and hypothesis. Then, the material and methods of the experimental study conducted will be described. It will be followed by the presentation of the results, discussion and limitations of the study, as well as the conclusion.

2. Literature review

2.1. Upper limb kinesiology related to climbing

A detailed description of the upper limbs' participation during climbing is already given (Holtzhausen and Noakes 1996). In an optimal grip on the hold, the fingers are flexed, the wrist is slightly extended with ulnar deviation, and the forearm is often held in full pronation. When gripping, the *flexor digitorum superficialis* and *profundus* tendons transmit the dynamic force to the fingers, which is generated by their muscle bellies in the forearm. It's above all the powerful flexion of the fingers that makes it possible to grip small edges of the holds on a rock. Furthermore, the hand grip is the first important movement to allow one to pull up toward the next hold. This involves using the *brachialis* and *biceps brachii* muscles to flex the elbow. Meanwhile, the forearm is held in a pronated position. For the pronation of the forearm, the *pronator teres* and the *brachioradialis* muscles are responsible (Biel and Dorn 2014). The *triceps brachii* works as the dynamic stabilizer of the elbow during the pull-up movement. When the trunk is pulled towards the handgrip, the upper arm can be extended towards ulnar direction to improve the mechanical advantage of the finger flexor tendons. However, during an ascent, a climber should sustain repeated hand grips; thus, repeated isometric contractions of finger flexors are required (Philippe et al. 2012).

2.1.1. Fingers

The climbers' tools for hanging from shallow ledges or latching onto the smallest cracks are the fingers, which undergo intermittent isometric contractions throughout the climb (Holtzhausen and Noakes 1996). The middle and interphalangeal joints will allow the application of forces to the fingertips, resulting in acute load on the flexor pulley system (Schöffl et al. 2003). The flexor pulley system consists of five annular and three cruciform tendons wrapped in a sheath which consists of fibrous tissue compaction (Crowley 2016; Holtzhausen and Noakes 1996). In figure 1 the positions and insertions of the finger flexor tendon pulleys (i.e., the tendons of the *m. flexor digitorum superficialis* (FDS) and of the *profundus* (FDP)) are depicted (Smith 2022). The A3 pulley is located over the proximal interphalangeal joint (PIP), and the A5 pulley is directly over the distal interphalangeal joint (DIP). The pulleys which are annular can further be divided into those which insert into the bone and those which are running into the volar plate. A2 and A4 pulleys running into the bone are also called true fibro-osseous pulleys. When performing pinching and grasping activities, these pulleys can withstand greater forces than the others. A1, A3, and A5, in turn, are more flexible and allow compression during flexion without impinging on the tendons. Moreover, the digital flexor sheath is described as a complex structure through which the flexor tendons of the fingers run (Crowley 2016). This structure is essential for the normal function of the flexor tendon and holds it close to the bone. Therefore, the tendon can effectively "turn around the corner" and transfer the force developed in the muscle-tendon unit into the movement which is generated at the phalanges.

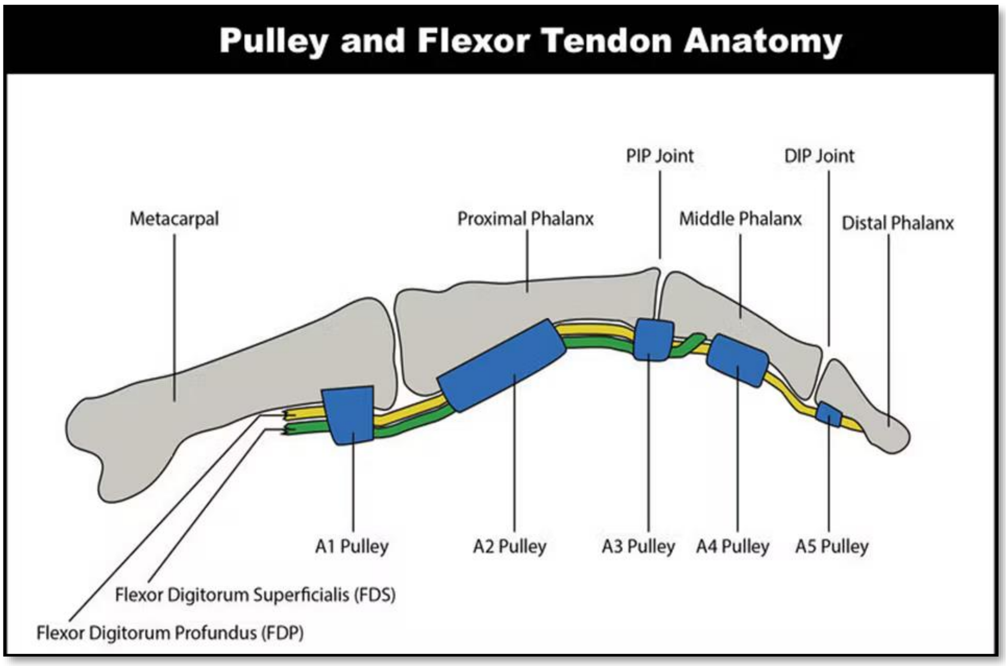

Figure 1: Position and insertions of the finger flexor tendon pulleys (Smith 2022:1).

One can say that kinesiological climbing has a particular feature. Usually, the human body is built to move and support its weight through the lower limbs. This relationship is inverted to some degree in climbing: a lot of the body weight often lies on the upper extremities. There are various possibilities for holding during climbing, but three types can be considered for the characterization of grips: crimps, pockets, and *slopers* (Schweizer 2001).

2.1.1.1. Crimp positions

The more complex the climb, the smaller the edges a climber will have to hold, thus higher the participation of fingers' distal phalanges in sustaining the body weight during the ascend (Crowley 2012; Bollen 1990). This type of gripping is called crimp and yields higher levels of stress on the flexor tendon pulleys. There are three types of crimping positions, as one can see in figure 2.

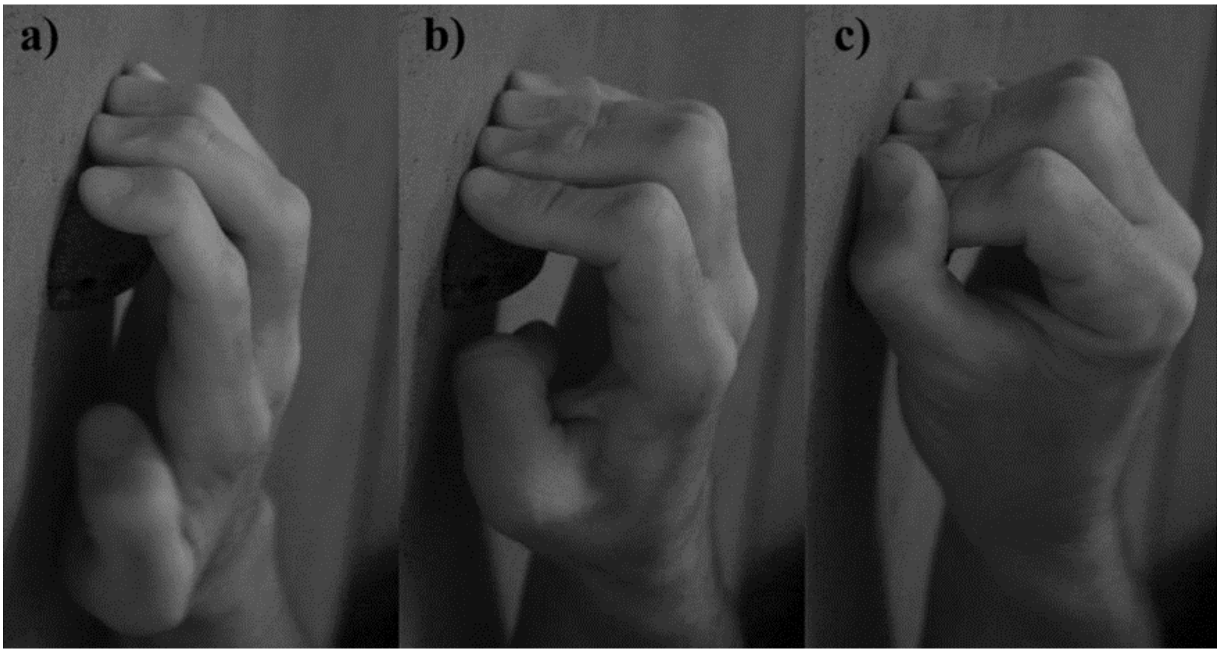

Figure 2: Crimping positions (Amca et al. 2012:670): a) open crimp; b) half crimp; c) full crimp

An open crimp position, as seen in figure 2a) is characterized by flexed finger joints (Amca et al. 2012). Grip in a half crimp position, as seen in figure 2b), is considered when the finger configuration for the PIP joint is flexed at approximately 90°, and there is a hyperextension of the DIP joints. Due to the strongly tensed flexor tendons of the fingers, such as the FDS and the FDP, there is an enormous force put on the finger pulley system (Crowley 2016; King and Lien 2017). Especially the FDP exerts high forces to the A2 pulley. It is reported that recreational climbers add approximately 380 N on the A2 pulley (Schweizer 2001). With this mentioned, repetitive stress, including these high forces, might lead to overuse syndromes, as well as injuries (Crowley 2016). In the full crimp grip like in figure 2c), all fingers are positioned as described above, except for the thumb. The thumb can often overlap the other fingers (especially index and middle fingers), which adds a significant effect on the maximum holding force (Crowley 2016; Torr et al. 2020). This is particular for this grip position and is referred to as closed crimp or full crimp grip, while when the thumb does not participate in the crimp, it is called half crimp grip position. The forces applied in each of these positions seem to be different. In full crimp, a climber might produce 494.8 ± 68.8 N, while 422.0 ± 42.9 N in half crimp grip (Quaine et al. 2011).

2.1.1.2. Finger-pocket position

In this position, there is a high load exerted on the middle and ring fingers, which are frequently the main fingers used in this grip position. When holding pockets, the fingers are extended in the metacarpophalangeal and proximal interphalangeal joints, as one can see in figure 3. Moreover, there is a strong flexion in the distal interphalangeal joint (Lutter et al. 2021).

Figure 3: Finger-pocket position (Lutter et al. 2021:5).

2.1.1.3. Slope-grip position

When climbers are faced with *slopers*, the challenge is to improve the friction between the skin of the hands and fingers in flat, round, or slope holds. Usually, this requires that the DIP joint is flexed and the PIP joint is adjusted to the shape of the hold, as seen in figure 4. It must be said that the PIP joint is mostly in a flexion of less than 40-60° (Lutter et al. 2021; Schweizer 2001).

Figure 4: Slope grip position (Lutter et al. 2021:5).

2.1.2. Forearm

Sustaining these grip positions depends on the action of the muscles of the forearm, which is often held in full pronation. When crimping, the FDS and FDP bring the most power to the fingers (Holtzhausen and Noakes 1996; Philippe et al. 2012). Individual and shared finger forces during half and full crimp positions are reported in table 1 (Quaine et al. 2011).

Table 1: Individual finger forces and shared finger forces of the index finger in combination with the thumb, the middle, ring and little finger (Quaine et al. 2011:51).

Full crimp	**Index Finger + thumb**	**Middle finger**	**Ring finger**	**Little finger**
Individual finger force	196.5 ± 35.0N	132.0 ± 28.1N	107.6 ± 17.0N	58.7 ± 16.6N
Shared finger force	39.6 ± 3.2 %	26.7 ± 4.1 %	22.0 ± 3.5 %	11.7 ± 2.5 %
Half crimp	**Index Finger + thumb**	**Middle finger**	**Ring finger**	**Little finger**
Individual finger force	102.6 ± 16.0N	134.1 ± 29.2N	112.9 ± 8.5N	72.4 ± 12.6N
Shared finger force	24.3 ± 3.2 %	31.6 ± 4.5 %	26.9 ± 2.2 %	17.1 ± 2.6 %

In half crimp, the middle and the ring finger have the highest individual finger forces. These results corroborate with a previous research study (MacDermid et al. 2004), which reported that during crimping, the middle finger contributed the most, followed by the ring and index finger. It is important to highlight, though, that none of these studies assessed the forces in hanging tasks. Hangings are important to demand the application of proper vertical forces from the fingers when gripping a hold (Morenas Martín et al. 2013), which would add to the methodological design a more ecological approach to real climbing situations.

Considering the knowledge that the FDS and FDP are transmitting the dynamic forces, it is important to have a closer look at the origin and insertion of these muscles. We do this in table 2. The FDS and FDP muscles are responsible for the flexion of the II. – V. finger. In addition, the FDS makes palmar flexion in the wrist possible. The extensor digitorum (ED) is considered not only a reference muscle but also the counterpart to the flexors. That the extensors play an important part in stabilizing the fingers and the wrist in a hanging position still needs to be studied. In his function, the ED is responsible for the extension of the II. – V. finger. Moreover, the ED supports the dorsal extension in the wrist. The function of the *musculus brachioradialis* (BR) lies in the flexion of the elbow. Furthermore, it is also supporting the pronation and supination of the forearm when resisting this movement. The *musculus pronator teres* is pronating the forearm and is as well supporting the flexion in the elbow (Biel and Dorn 2014).

The following table 2 is based on the anatomy guide (Biel and Dorn 2014):

Table 2: Forearm muscles considered in this thesis including their function, insertion and origin (Biel and Dorn 2014:127–142)

Muscle	Function	Insertion (I), Origin (O)
M. brachioradialis	Flexion of the elbow, helping with pronation and supination of the forearm	**I:** *processesus styloideus radii* **O:** *crista supracondylaris humeri lateralis*
M. pronator teres	Pronation of the forearm, helping with the flexion of the elbow	**I:** in the middle of the lateral *radius* **O:** common flexor tendon of the medial epicondyle *humeri*, *processus coronoideus ulnae*
M. flexor digitorum profundus	Flexion of the 2. – 5. finger, helping with palmar flexion	**I:** basis of the distal phalangeal and the palmar side of the 2. – 5. finger **O:** ventral and medial side of the proximal 4/3 of the *ulna*
M. flexor digitorum superficialis	Flexion of the 2. – 5. finger, palmar flexion	**I:** sides of the medial phalangeal of the 2. – 5. finger **O:** common flexor tendon of the medial epicondyle *humeri*
M. extensor digitorum	Extension of the 2. – 5. finger, helping with dorsal extension	**I:** Basis of the medial and distal phalangeal of the 2. -5. finger **O:** common extensor tendon of the lateral epicondyle *humeri*

Regarding the function of each muscle and because of the fact that in this thesis we use the half crimp finger configuration where the PIP joints are flexed around 90° and the DIP joints are hyperextended, we examine the finger flexor muscles more detailed in chapter 2.4.1., muscle fatigue in climbing.

Having covered the kinesiology of the upper limb and its relationship to sport climbing, this thesis can further describe relevant issues related to the physiological and biomechanical aspects related to this activity.

2.2. Physical and physiological demands of sport climbing

Sport climbing is characterized as a forceful-endurance activity in which the main resistance force is the body weight. Moreover, the effort which is exerted during climbing is of intermittent nature, defined by various isometric muscle contractions (Ozimek et al. 2017). In sport climbing, athletes would spend between 2 and 7 minutes in intermittent activity (Macleod et al. 2007; Watts 2004), and the exercise-to-relaxation ratio is described as around 1:4 (White and Olsen 2010), in which 40% of the exercise time would be in a static support position (Watts 2004). Bouldering is considered more strength and power dependent, and the exercise-to-relaxation ratio for the repeated finger isometric flexions are reported to be 13:1 seconds (White and Olsen 2010). Thus, climbing can be described as an acyclic anaerobic-aerobic activity (Bechtel 2020). The main energy systems demanded in climbing are aerobic and anaerobic alactic, regardless of training status or skill level (Bertuzzi et al. 2007). The following values are based on the study of Bertuzzi et al. (2007), who calculated the aerobic and anaerobic alactic energy system on the basis of oxygen uptake as well as the component of rapid excess oxygen uptake in blood after an effort. On a moderate route, which is considered a 15 on the IRCRA scale, the aerobic metabolic cost was at 45.8 ± 8.4 kJ and 34.6 ± 7.1 kJ of the anaerobic alactic metabolic costs. A difficult route was considered a 19 on the IRCRA scale and did cost the elite climbers around 41.9 ± 7.4 kJ of the aerobic and 35.8 ± 6.7 kJ of the anaerobic alactic metabolic costs. The physiological impact of some additional features related to climbing difficulty have also been studied. The increase in climbing difficulty demands a higher level of grip endurance when compared to hand grip strength. Thus, demands such as upper limb muscle strength and capability of resisting fatigue, especially for the finger flexors, are widely acknowledged as determinants of climbing performance (Ozimek et al. 2017; Watts 2004). Additionally, increasing the steepness of climbing walls is directly related to increases in heart rate, although the maintenance of the oxygen uptake (Watts 2004).

2.3. Determinants of success in climbing

2.3.1. Physiological and biomechanical determinants

According to Stien et al. (2019), physiological and biomechanical determinants of performance are not easy to differentiate. A previous study has described how finger force is produced when performing hangings is dependent on finger-hold contact technique because depending on the hold depth and the grip technique, climbers are able to apply more or less vertical and antero-posterior forces (Amca et al. 2012). Interestingly, the hand-forearm posture differs across the different grip techniques, i.e. slope versus crimp, while performing the task. While using a crimp grip, participants present a nearly vertical hand positioning and a larger wrist extension, which is caused by the increased forearm angle (see figure 5). While using the slope, the hand and the forearm present a smaller wrist extension through a more inclined forearm position, to keep the body balanced while hanging. Thus, each grip position requires specific biomechanical adaptations from climbers as strategies for greater finger-hold interaction to allow for task completion.

In climbing, as presented in the previous topic of this thesis, forearm/ handgrip ability to endure to maintain the grip during climbing is a key feature for the sport (Giles, Rhodes, and Taunton 2006). Climbers present higher forearm endurance compared to non-climbers (Stien et al. 2019), and the ones performing on an elite level have higher time to exhaustion (770 ± 385 s) than expert climbers (408 ± 150 s) (España-Romero et al. 2009). Thus, it is hypothesized that climbing develops forearm vasodilatory capacity, so there is a higher hyperemia or blood flow in the forearm during the contraction phase of gripping (Saul et al. 2019; Magiera et al. 2013; Stien et al. 2019). Forearm oxidative capacity is also associated with red-point level, or ability to climb more difficult routes, thus an important factor for climbing performance (Fryer et al. 2016). Success in climbing is also dependent on grip strength capacities which differs among elite, recreational, and non-climbers (Saul et al. 2019), and it is highly task-specific. Handgrip strength measured from hand dynamometers has weak correlation with climbing performance (Baláš et al. 2014; Quaine, Vigouroux, and Martin 2003), once it does not correspond to grip positions used in climbing (Watts 2004). Previous research has tested climbers during isometric finger hanging position on 2.5 mm and 4.0 mm ledges and performances vary according to skill level (Ozimek et al. 2017). Another issue to be considered when discussing climbers grip strength is related to the use of absolute and relative strength values. According to Giles et al. (2006), absolute hand-related strength is not significantly higher in elite climbers when compared to other skill levels, but strength relative to body weight is, indicating that not only grip strength but also reduced body mass can be advantageous to climbing.

2.3.2. Anthropometric determinants

The anthropometric features of athletes are considered determinants of performance in many sports and have been widely discussed and described in climbing (Giles et al. 2006; Grant et al. 2001; Mermier 2000; Michailov, Mladenov, and Schöffl 2009; Sheel 2004). Previous data on climbers' anthropometry during competitions have been reported for the semi and finalists of the lead world cup (Watts, Martin, and Durtschi 1993) and the bouldering world cup (Michailov et al. 2009). Lead world cup competitors had an average body height of 177.8 and 179.3 cm for semi and finalists, an average body weight of 66.6 and 62.6 kg, and an average fat-free mass of 63.5 and 59.3 kg, respectively. The literature indicates that lower weight and height, as well as lower body mass index and a small percentage of body fat, are associated with high-performance levels in climbing, and it seems to be valid in terms of both indoor competitions and rock-climbing accomplishments (Ignjatović et al. 2017; Michailov et al. 2009; Tomaszewski, Gajewski, and Lewandowska 2011; Watts 2004). Additionally, although increased ape index (ratio of arm span to height) is described to be helpful in climbing but not considered a determinant of performance (Saul et al. 2019).

2.4. Muscle Fatigue

Muscle fatigue is often defined as the incapacity to maintain the required or expected work (Edwards 1981; González-Izal et al. 2012). It is an exercise-induced phenomenon, where there is a loss of force-generating capacity during voluntary contractions, and which may or may not result in a loss of task performance (Enoka and Duchateau 2008; Søgaard et al. 2006).

Muscle fatigue can be divided into two types: central and peripheral fatigue. Central fatigue is the decrease in voluntary activation of the muscle due to a decrease in the recruited motor units and their discharge rate. Peripheral fatigue refers to changes in the neuromuscular transmission and propagation of muscle action potential and also involves the decrease in the contractile force of the muscle fibers (González-Izal et al. 2012). Such neuromuscular manifestations of fatigue reflect the adaptations from the central and peripheral nervous systems, which can be assessed in sustained contractions through electromyography (EMG). Under fatigue, a muscle will present a decrease in its conduction velocity (Enoka and Duchateau 2008) and frequency of discharge of motor units (Dideriksen, Enoka, and Farina 2011). In the EMG signal, this would reflect in a decrease of the mean frequency (Bigland-Ritchie, Donovan, and Roussos 1981) and a variable effect on the signal amplitude once it depends on factors such as the muscle involved and the level of contraction (Gerdle, Larsson, and Karlsson 2000).

During the development of fatigue, muscles involved in the exercise/contractions will change patterns of activation as a result of adaptations to this process (Enoka and Duchateau, 2008). Regarding muscle activation patterns, literature has described such adaptations to be related to activity alternation across synergistic muscles for contractions above 5% maximal voluntary contraction (MVC) (Kouzaki et al. 2002) to maintain force output, co-activation with antagonists for contractions up to 60% MVC (Lévénez et al. 2005) to stabilize the involved joint, contralateral muscle activation (Todd et al. 2003) possibly to activate ipsilateral projections or contralateral callosal connexions, and increased variability of activation within the task (Baudry et al. 2007).

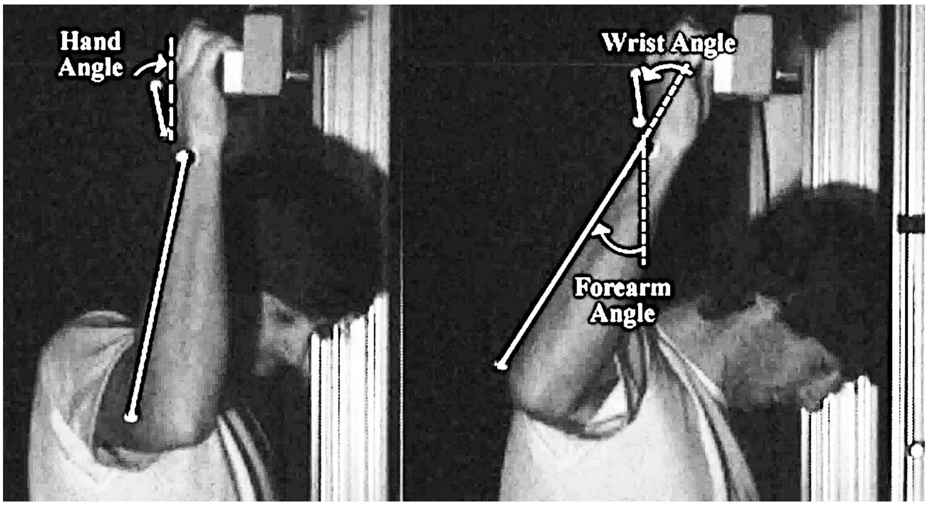

Figure 5: Illustration of the analyzed angles, whereas hand and forearm angles were gathered from the corresponding markers (left). The wrist angle was considered as the angle formed by the hand and the forearm markers (right).(Amca et al. 2012:672)

2.4.1. Muscle fatigue in climbing

Literature presents some important information regarding upper-limb during sustained isometric contractions in climbers, especially for training guidelines purposes. Watts et al. (2008) reported that longer recovery periods are needed after fatiguing maximal body-weight hangs using open grip in a *sloper* bar. Authors tested 1-min and 3-min periods for recovery after maximal hangings, and reported peak and integrated EMG of the forearm flexors. Peak EMG and mean finger force did not change across repetitions neither for 3-min nor for 1 min- recovery time, while integrated EMG did decrease for both recovery strategies. However, there was an overall decline in hanging time when climbers had less time to recover in between trials.

Other upper limb muscles, accessories to the hanging posture while climbing, have been also investigated. The *brachioradialis* and the *teres major* EMG activity were recorded during isometric half-way pull-up, with elbows flexed at 90° and the shoulders abducted at 90°, and compared to a sequence of dynamic pull-ups. The dynamic task led to higher fatigue than the sustained isometric contraction, presenting a shorter time to failure and higher levels of muscle activation manifestations of fatigue (Boccia et al. 2015).

The current findings on determinants of performance and fatigue-related issues in climbing are important steps towards the understanding of the sport and how to achieve its excellence. However, it clearly indicates that the step further on that path should look at the behavioral aspects associated to actual climbing and climbing-specific tasks, by integrating the biomechanical and physiological aspects with a motor-control view.

2.5. Coordination and its analysis

Typically, the upper body extremities during climbing often aim for overhead reaches. To ascend, climbers have to adapt wrists, elbows, and shoulders to intermittently hold on to static positions in postures that demands high level of controlling strategies (MacLean and Dickerson 2019). Three factors are described as important to keep a climber on the wall: postural stability, accuracy, and force. Postural stability regards the control of the body center of mass (CoM) while climbing. In static as well as dynamic movements, advanced and experienced climbers show greater distance between the CoM and the wall to be able to hold their bodies in position longer when compared to beginners. Accuracy is related to the range of body movements a climber is able to perform to keep progressing over a climb. Experienced climbers use wider ranges of lower and upper extremity movements and need fewer exploratory movements when compared to beginners. (Saul et al. 2019; Russell, Zirker, and Blemker 2012). The force aspect has been described through physiological and biomechanical lenses, but also has a role through the motor control approach. As mentioned before, the optimal fingers' force exertion depends on the type of grip, and this is because it defines the whole-body segments alignment and posture to maintain the task. Also, advanced and experienced climbers present higher optimization of muscle activation patterns when compared to beginners, thus, they are able to save energy and maintain tasks for longer time (Russell et al. 2012; Saul et al. 2019).

Coordination involves bringing the multiple independent motions allowed to the body at each level or scale into proper relations (Turvey 1990). Looking at the integration between motor unit firing patterns, force production at the muscle level and joint kinematics is an example of the multiple scales of space and time in which a climber has to organise in functional units to perform. At the musculoskeletal level, it can be studied from the synchronicity of motor units to the coordination of muscle force to the oscillatory features of the musculoskeletal connections (Zehr 2017). At the limbs' kinematics level, skill mastering processes can be identified by movement fluency, for example (Boschker and

Bakker 2002; Orth, Davids and Seifert 2016), which can be inferred by coordination measures (Robertson et al. 2014).

Expertise in climbing is related to a high capacity of sustaining longer in isometric positions (Saul et al. 2019). And, as previously discussed, fatigue is a phenomenon which causes impairment of work capacity, and does that at different levels of the human body functional mechanisms (metabolic, sensory-motor, cognitive, etc.). Understanding the patterns of coordination during climbing-specific sustained isometric tasks can reveal the strategies underlying the organization and control of the upper limb system, tying together the biomechanical and physiological aspects related to climbing performance.

3. Research question

The previous overview described important characteristics of the mechanical, physical, and physiological aspects related to most modalities of climbing and their performance. In general, climbing is an intermittent whole-body vertical activity in which forearm muscles strength and endurance are determinant components of performance. Specifically, it is well known how such physical and physiological capacities are described according to aspects as climbing modality (Michailov et al. 2009), climbing difficulty level (Ignjatović et al. 2017), and gender (Watts et al. 1993). However, the integration between physical/physiological capacities and motor control aspects are still being explored in the sport. Deepening such understanding would be important to reveal the behavioural mechanisms underlying the body adaptation and organisation processes under fatigue. Therefore, the aim of this thesis is to assess and describe climbers' upper body muscle activation and coordination strategies during hanging under fatiguing conditions. It is hypothesized that, to correspond and adapt to the development of muscle fatigue while continuously hanging on a narrow edge, a very common task during climbing performance, climbers will yield specific upper body postural adjustments which can be verified through joint coordination patterns.

4. Material and Methods

4.1. Sample

Thirteen male climbers (26 ± 5.2 years age; 178 ± 5.8 cm body height; 72 ± 6.9 kg body weight, 5 ± 4.7 ape index) voluntarily participated in the study. All participants had to have red-pointed at least one 7a+ (french scale) in a sport climbing route or a 6c+ boulder (french scale) in the past year, thus achieving a minimum of 19 points in the IRCRA scale (Saul et al. 2019). The sample of the present study scored 22 ± 3.3. In addition, the subjects should already have experience in fingerboard training and should present no recent upper-limb injuries.

The study was conducted according to the Declaration of Helsinki and was approved by the Ethics Committee of the University of Vienna (reference number: 00690).

4.2.3. Experimental protocol

The experimental protocol involved a warm-up followed by the maximal hanging task for all participants, which were performed in the same session. The warm-up lasted 15 minutes and consisted of executing jumping jacks, upper extremity mobilization, forearm rotation, shoulder abductions, shoulder pulls, finger strengthening, and pull and push-ups. The experimental task consisted of two maximal hangings until failure in a custom-built hangboard (figure 6). Thus, participants should hang with both hands on a 20 mm ledge for as long as possible, using a half-crimp position for the fingers, wrist pronated, arms extended, and maintaining horizontal sight. The test ended when the participants couldn't maintain the required body position or fell off the hangboard. In between each trial, a 10-min recovery time was given (López-Rivera, González-Badillo and España-Romero 2022; Watts et al. 2008).

Figure 6: Self-made stable hangboard, attached to the ceiling with metal pipes (20 mm grip depth).

4.2. Measurements

4.2.1. Electromyography (EMG)

Surface Electromyography (sEMG) from 12 muscles of the left and right upper limbs and trunk were measured with a wireless device (Cometa®, Milan, Italy) at 1,000 Hz. Before attaching all Ag/AgCl electrodes, each participant had the skin region where sEMG was measured properly, shaved, and cleaned. Table 3 describes the muscles in which the electrical activity was measured, with its placement directions and the reference.

Table 3: Electrode placement for all six muscles including literature references

Muscle	Electrode placement	Literature
Thorax Front		
Pectoralis major (sternal)	Electrode is placed 6 cm above the nipple and a little bit more on the lateral side. It should run parallel to the muscle fibers.	(MacLean and Dickerson 2019)
Thorax Back		
Trapezius transversalis (middle)	Electrode is placed at 50% between the medial border of the scapula and the spine, at the level of T3. It should run parallel to the muscle fibers.	(H.J. Hermens and Freriks 2022)
Upper arm		
Biceps brachii	Electrode is placed on the line between the medial acromion and the fossa cubitalis at 1/3 from the fossa cubitalis. It should run parallel to the muscle fibers.	(H.J. Hermens and Freriks 2022)
Forearm		
Brachioradialis	Electrode is placed 4 cm distally from the lateral epicondyle of the elbow on the medial fleshy mass that covers that area. It should run parallel to the muscle fibers.	(Merlo, Bò, and Campanini 2021)
Flexor digitorum superficialis	First the participant had to flex four fingers against external resistance while palpating the forearm over the contracting muscle. The participant had to have a voluntary stable wrist. Then electrodes could be placed parallel to the muscle fibers, on the muscle belly.	(Quaine et al. 2003)
Extensor digitorum	Electrode is placed at ¼ point on a line drawn from the lateral epicondyle to the styloid process of the ulna. The EMG should run parallel to the muscle fibers.	(Quaine et al. 2003)

4.2.2. Kinematics

The upper body kinematics were obtained with a 12-camera 3D motion capture system (Vicon®, Oxford, UK). For the present study, the upper limb model of Nexus (Vicon Motion Systems, Oxford, UK) was used. The model is an extended version of the conventional Plug-in-Gait model for the upper limbs, which is written in Vicon BodyLanguage (Vicon Motion Systems 2007). Table 4 lists all markers used in the upper-body model and indicates their placement accordingly.

Table 4: Marker placement. Placement according to the Vicon upper limb model product guide (Vicon Motion Systems 2007:7–9).

Marker	Definition	Placement
Finger		
(L/R)DPS	(Left/Right) distal phalanx segment	Distal phalanx segment of the middle finger
(L/R)MPS	(Left/Right) medial phalanx segment	Medial phalanx segment of the middle finger
(L/R)PPS	(Left/Right) proximal phalanx segment	Proximal phalanx segment of the middle finger

Hand		
(L/R)Ossa Metacarpi A	(Left/Right) Ossa metacarpi marker A	Just below the left/right second metacarpus
(L/R)Ossa Metacarpi B	(Left/Right) Ossa Metacarpi marker B	Just below the left/right fifth metacarpus
(L/R)Ossa Carpi	(Left/Right) Ossa Carpi	On the left/right ossa carpi which forms a triangle with (L/R) OssaMetacarpi A and (L/R) OssaMetacarpi B
Forearm		
(L/R)WRA	(Left/Right) wrist marker A	At the thumb side of left/right radial styloid attached symmetrically with a wristband on the posterior of the left/right wrist, as close to the wrist joint center as possible
(L/R)WRB	(Left/Right) wrist marker B	At the little finger side of left/right ulnar styloid attached symmetrically with a wristband on the posterior of the left/right wrist, as close to the wrist joint center as possible
(L/R)FRA	(Left/Right) forearm	On the lateral left/right forearm (according to the picture in the manual)
Elbow		
(L/R)MEP	(Left/Right) medial epicondyle	Left/right humerus medial epicondyle
(L/R)ELB	(Left/Right) lateral epicondyle	On the lateral (left/right) epicondyle approximating the elbow joint axis
Upper arm		
(L/R)SHO	(Left/Right) shoulder	On the (left/right) acromion-clavicular joint
(L/R)UPA	(Left/Right) upper arm marker A	On the lateral upper left/right arm (according to the picture in the manual)
(L/R)UPB	(Left/Right) upper arm marker B	On the lateral upper left/right arm (according to the picture in the manual)
(L/R)UPC	(Left/Right) upper arm marker C	On the lateral upper left/right arm (according to the picture in the manual)
Thorax		
C7	7th cervical vertebra	On the spinous process of the 7th cervical vertebra
T10	10th thoracic vertebra	On the spinous process of the 10th thoracic vertebra
STRN	Sternum	On the xiphoid process of the sternum
CLAV	Clavicle	On the jugular notch where the clavicles meet the sternum

Figure 7 visualizes an example of the upper limb marker as well as the sEMG placement, with a frontal and dorsal view.

Figure 7: Upper Limb Model marker placement and sEMG placement – front and back view

4.2.4. Data processing

sEMG raw data were first filtered with a bandpass (4 – 400 Hz), 4th order Butterworth filter. The signals were then demeaned and rectified. A low-pass, 4th order Butterworth filter with a cut-off frequency of 6 Hz was applied. Amplitude-normalization of the sEMG data was performed to its peak value during the fatiguing task.

The kinematic 3D data post-processing after the motion capture was performed via the Vicon Nexus®. The static trails were used for labelling the markers as well as filling the eventual tracking gaps found in the recordings. Furthermore, for each trial, a starting and ending point were defined to create cycles. This was done in order to avoid processing unnecessary data and getting to the region of interest. This made it possible to provide more precise information and make it comparable across participants. The starting point was at 4 sec before the subject was sustaining the body weight on to the hangboard and ended 4 sec afterwards when the contact with the hangboard was lost. Both sEMG and kinematics were also time-normalized for further analysis and interpretation of the results.

4.2.5. Data analysis

From the processed sEMG for all twelve muscles, including the *biceps brachi* (BB), the *brachioradialis* (BR), finger extensors (EDS), and flexors (FDS), the *pectoralis major* (PM) and the *trapezius transversus* (TT) muscle, two variables were calculated to explain the neuromuscular behavior of climbers under fatiguing hangs. The first was a time-domain variable, the root mean square of the sEMG signal (RMS), which reflects the mean power of the signal (Konrad 2006). The RMS was calculated using a moving mean of 50 ms. The second variable was in the frequency domain, the median frequency (MF), which divides the area of the total power spectrum into two equal parts (Konrad 2006). RMS and MF were calculated throughout the whole task cycle.

The coordination strategies adopted by the climbers during the hangs until fatigue were represented by the vector coding (VC) technique. Vector coding is calculated by the following equations. The first equation (1) enables a derivation of the coupling angle, including the correction factor (Zehr 2017).

(1) $\gamma_{j,i} \; = \; \text{atan}\left(\frac{\theta \; distal_{j,i+1} - \theta distal_i}{\theta \; proximal_{j,i+1} - \theta proximal_i}\right)$

Zehr (2017, S. 22) stated that: “Coupling angles (ϒ) at a given instant *(i)* are computed from the angle-angle trajectory constructed for cycle j by taking the arctangent of the angle subtended between the vector joining two adjacent points and the relative horizontal plane.”. The following options are presented by Zehr (2017, S. 23):

“IF $(\theta \; distal_{j,i+1} - \theta distal_i) = 0$ AND $(\theta \; proximal_{j,i+1} - \theta proximal_i) > 0 \quad \gamma_{i=90°}$

IF $(\theta \; distal_{j,i+1} - \theta distal_i) = 0$ AND $(\theta \; proximal_{j,i+1} - \theta proximal_i) < 0 \quad \gamma_{i=-90°}$

IF $(\theta \; distal_{j,i+1} - \theta distal_i) < 0$ AND $(\theta \; proximal_{j,i+1} - \theta proximal_i) = 0 \quad \gamma_{i=-180°}$

IF $(\theta \; distal_{j,i+1} - \theta distal_i) = 0$ AND $(\theta \; proximal_{j,i+1} - \theta proximal_i) = 0 \quad \gamma_{i=NaN}$ “

In addition to the explanation of the equation above, the angle γ is reaching from 0° to 360°. According to Zehr (2017, S.23): “Coupling angles define the magnitude and direction of frame-to-frame vectors. Each single vector characterizes inter-segment/joint-coordination patterns.” The coupling angles are defined as follows in table 5:

Table 5: Classification of coordination pattern based on the coupling angles (Robertson et al. 2014:312; Zehr 2017:23).

Coordination pattern	Coupling angles
In-phase	[22.5° ≤ γ < 67.5°, 202.5° ≤ γ < 247.5°]
Rotation of the proximal segment/joint	[67.5° ≤ γ < 112.5°, 247.5° ≤ γ < 292.5°]
Anti-phase	[112.5° ≤ γ < 157.5°, 292.5° ≤ γ < 337.5°]
Rotation of the distal segment/joint	[0° ≤ γ < 22.5°, 157.5° ≤ γ < 202.5°, 337.5° ≤ γ ≤ 360°]

Thus, when in-phase, the coupled joints are rotating in the same direction, whereas in anti-phase, the coupled joints are rotating in the opposite direction. If coupling angles are within the range of the rotation of the distal segment/joint, the distal segment or joint is dominant. Moreover, if coupling angles are considered within the range of the rotation of the proximal segment or joint, the proximal segment is the dominant one (Robertson et al. 2014).

The proximal-distal couples for left and right arms and the respective planes of movement considered were as follows:

- In the sagittal plane (flexion and extension), three coordination patterns were calculated: the wrist-elbow, wrist-shoulder, and the elbow-shoulder.
- Wrist-shoulder coordination data was also conducted in the frontal plane (abduction and adduction, radial and ulnar deviation). In the transversal plane (internal and external rotation), elbow-shoulder coordination patterns were investigated.

To understand the effect of fatigue in the upper limb muscles activation, as well as in the coordination patterns, the first and last 20% of the cycle were compared. These two timespans in the cycle represent non-fatigued (1-20%) and fatigued (80-100%) states. To perform such, data normality was tested using the Kolmogorov-Smirnov (KS)-test. When the data were found normally distributed, a paired t-test was applied to compare the non-fatigued to fatigued state, while when the data was not normally distributed, comparison was performed using Wilcoxon signed ranks test. For all tests, it was considered $p<0.05$.

Data processing and analysis were performed using custom scripts developed in Matlab®. In addition, the SPSS® (IBM SPSS statistics) was used for statistics.

5. Results

5.1. Electromyography

The descriptive statistics for MF and RMS results during fatiguing hanging in climbers are depicted in table 6. The median frequency (MF) was tested normally distributed in the first 20% of the cycle for the *brachioradialis* (D(13) = 0.088, p = 0.2), finger extensor (D(13) = 0.153, p = 0.2) and *trapezius* (D(13) = 0.118, p = 0.2). MF in a fatigued state was tested normally distributed with the *biceps* (D(13) = 0.107, p = 0.2), the *brachioradialis* (D(13) = 0.175, p = 0.1), and the *trapezius* (D(13) = 0.094, p = 0.2).

According to the Kolmogorov-Smirnov test, the root mean square (RMS) in the first 20 % of the cycle was tested normally distributed for the *biceps* (D(13) = 0.090, p = 0.2), the *brachioradialis* (D(13) = 0.188, p ≈ 0.1), the finger extensors (D(13) = 0.165, p ≈ 0.2) and flexors (D(13) = 0.182, p ≈ 0.1) as well as the *pectoralis major* (D(13) = 0.163, p ≈ 0.2). In the last 20 %, only the *biceps* (D(13) = 0.127, p = 0.2) was tested normally distributed.

Table 6: Data normality of MF and RMS

Data Normality

			Median Frequency (Hz)		Root Mean Square (RMS)	
Muscle	**Condition**	**df**	**Statistic**	**p value**	**Statistic**	**p value**
Biceps	Unfatigued	13	0.197	0.041	0.09	.200*
	Fatigued	13	0.107	.200*	0.127	.200*
Brachioradialis	Unfatigued	13	0.088	.200*	0.188	0.061
	Fatigued	13	0.175	0.109	0.198	0.039
Finger extensor	Unfatigued	13	0.153	.200*	0.165	0.158
	Fatigued	13	0.220	0.012	0.224	0.01
Finger flexor	Unfatigued	13	0.201	0.033	0.182	0.083
	Fatigued	13	0.290	<.001	0.226	0.009
Pectoralis major	Unfatigued	13	0.193	0.049	0.163	0.172
	Fatigued	13	0.218	0.014	0.269	<.001
Trapezius	Unfatigued	13	0.118	.200*	0.195	0.044
	Fatigued	13	0.094	.200*	0.253	0.002

* significant difference between fatigued and unfatigued

5.1.1. Median Frequency (MF)

MF of the upper limb muscles during the fatiguing hang test is depicted in figure 8. In table 7 MF descriptive data can be seen. There was a significant decrease in MF for the *biceps* (z = -3.92, p<0.001), *brachioradialis* (t(12) = 10.68, p<0.001), finger extensor (z = -3.88, p<0.001) and flexor (z = -3.81, p<0.001) from the beginning (unfatigued state) to the end (fatigued state) of the task. *Trapezius*, on the other hand, showed increased MF (t(12)= -4.63, p<0.001) with fatigue, while pectoralis major (z = -0.75, p =0.4) showed no significant difference considering the beginning and end of the task. Cohen's D values for the *brachioradialis* (d = 2.39) and the *trapezius* (d = -1.04) indicate large effects (d = 0.80). For the Wilcoxon test, data the effect size was calculated according to Pallant (2007). For the *biceps* (r = -0.62), the finger extensors (r = -0.61), and flexors (r = -0.60) using Cohen's D criteria, a large effect (d = 0.80) was given. For the *pectoralis major* (r = -0.12), a small effect size (d = 0.20 for Cohen's D, d = 0.10 for Pearson's r) was investigated.

Table 7: Descriptive data and MF of climbers' upper limb muscles during a fatiguing hanging test on a 20mm -edge hangboard.

Median Frequency (Hz)

Muscle	Condition	Mean ± Std	p value
Biceps	Unfatigued	0.29 ± 0.04	< 0.001*
	Fatigued	0.24 ± 0.02	
Brachioradialis	Unfatigued	0.31 ± 0.02	< 0.001*
	Fatigued	0.25 ± 0.02	
Finger extensor	Unfatigued	0.35 ± 0.03	< 0.001*
	Fatigued	0.24 ± 0.03	
Finger flexor	Unfatigued	0.32 ± 0.03	< 0.001*
	Fatigued	0.21 ± 0.04	
Pectoralis major	Unfatigued	0.19 ± 0.03	0.4
	Fatigued	0.18 ± 0.03	
Trapezius	Unfatigued	0.21 ± 0.02	< 0.001*
	Fatigued	0.24 ± 0.03	

* significant difference between fatigued and unfatigued

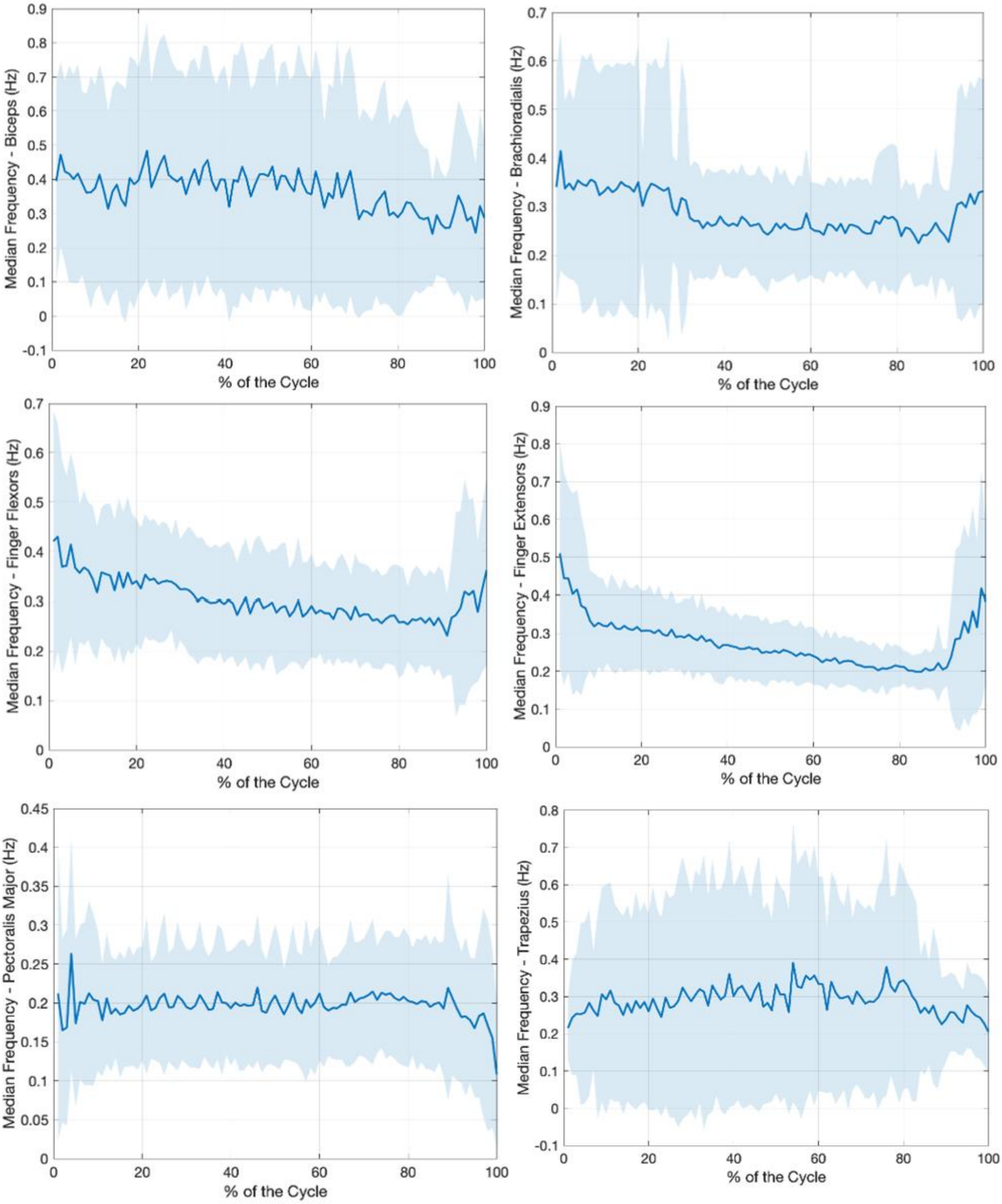

Figure 8: Mean course (blue line) and standard deviation (shaded region) of upper limb muscles' MF (Hz) during fatiguing hanging test in climbers.

5.1.2. Root Medium Square (RMS)

The RMS of the upper limb muscles of climbers across the whole hanging task is shown in figure 9, while table 8 shows its descriptives. The *biceps* (t(12) = -16.33, p < 0.001) with a large effect size of d = -3.6, the *brachioradialis* (z = -2.24, p = 0.02), the finger extensors (z = -2.09, p = 0.04), the *pectoralis major* (z = -3.51, p < 0.001) and the *trapezius* (z = -3.92, p < 0.001) showed a significant difference between unfatigued and fatigued states. The *brachioradialis* (r = -0.88), finger extensor (r = -0.87), and flexors (r = -0.92) did show, on the basis of Cohen's D criteria, a large effect (d = 0.80) size when calculated according to Pallant (2007). The *trapezius* (r = -0.71) did show a medium effect (d = 0.50) size according to Cohen's D criteria. Although on the basis of Pearson's r criteria, the *trapezius* did also show a large effect size (d = 50) (Brydges 2019). The *pectoralis major* (r = 0,16), however did show a small effect size (d = 0.20 for Cohen's D, d = 0.10 for Pearson's r). All muscles showed increased RMS at the end of the hanging, with the exception of the finger flexors (z = -1.49, p = 0.14), which did not show any significant difference between the beginning and end of the task.

Table 8: Descriptive data and RMS of climbers' upper limb muscles during a fatiguing hanging test on a 20mm -edge hangboard

Root Mean Square (Hz)

Muscle	Condition	Mean ± Std	p value
Biceps	Unfatigued	0.08 ± 0.02	> 0.001*
	Fatigued	0.58 ± 0.15	
Brachioradialis	Unfatigued	0.55 ± 0.41	0.025*
	Fatigued	1.02 ± 0.51	
Finger extensor	Unfatigued	0.53 ± 0.26	0.037*
	Fatigued	0.85 ± 0.43	
Finger flexor	Unfatigued	0.84 ± 0.54	0.135
	Fatigued	1.20 ± 0.59	
Pectoralis major	Unfatigued	0.12 ± 0.06	<0.001*
	Fatigued	0.34 ± 0.14	
Trapezius	Unfatigued	0.14 ± 0.05	< 0.001*
	Fatigued	0.53 ± 0.12	

* significant difference between fatigued and unfatigued

Figure 9 presents the curves of root mean square for all muscles during the whole hanging cycle. It is interesting to note that towards the end of the hanging trail, the RMS values decrease again after having increased for the maiority of the time.

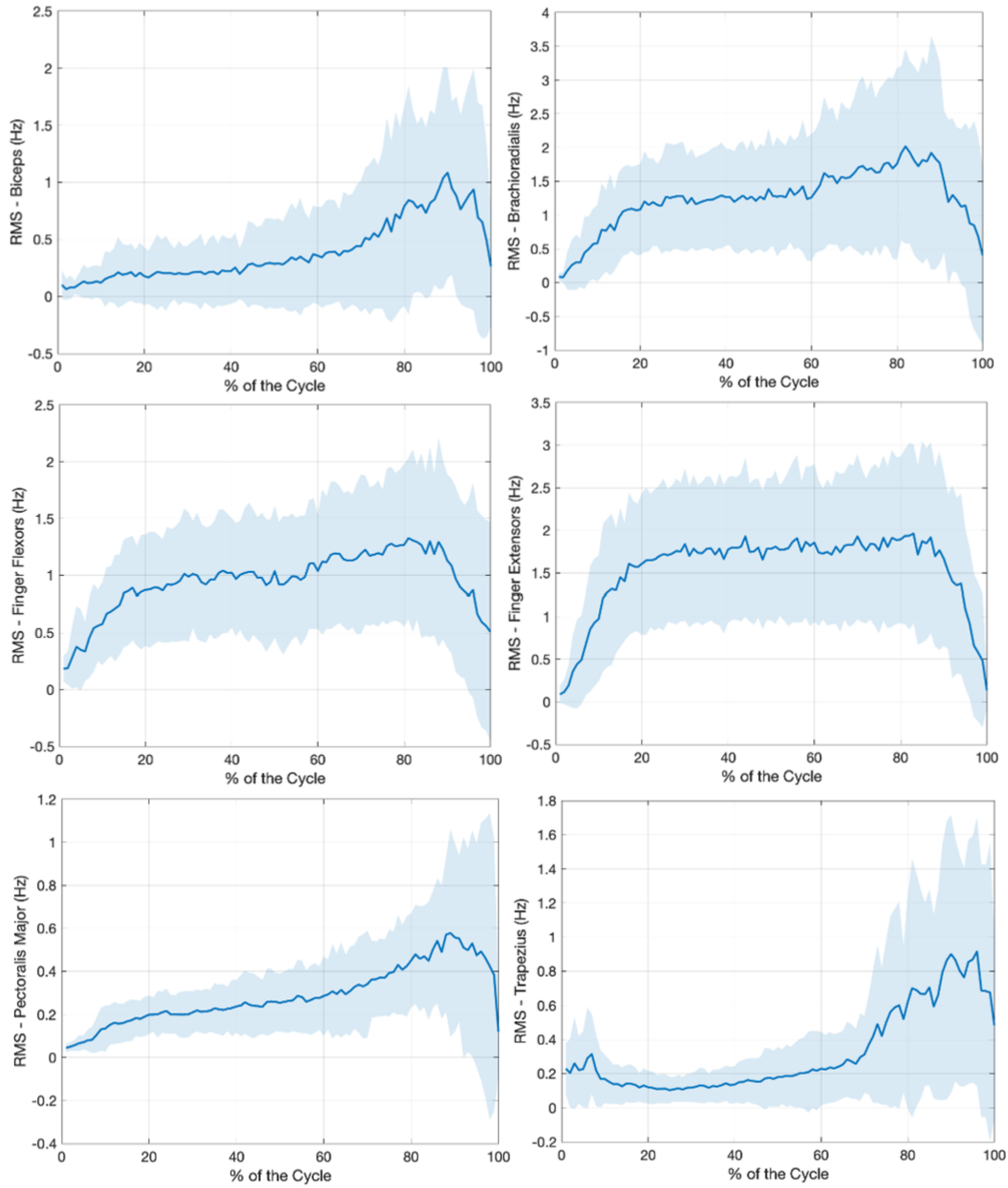

Figure 9: Mean course (blue line) and standard deviation (shaded region) of upper limb muscles' RMS (Hz) during fatiguing hanging test in climbers.

5.2. Kinematics

5.2.1. Upper limb coordination data

Except for the elbow-shoulder in the sagittal plane (coupling 3) (D(13) = 0.160, $p \approx 0.2$) and in the transversal plane (coupling 5) (D(13) = 0.182, $p \approx 0.1$), p-values for coupling 1, 2 and 4 are 0.2 in the Kolmogorov-Smirnov-test (see table 9). Based on the results, a paired samples test was used to test for differences in coordination in non-fatigued and fatigued states.

Table 9: Test of normality for kinematic data

Tests of Normality

		Kolmogorov-Smirnov[a]		
		Statistic	**df**	**Sig.**
Coupling 1	20_WE_S_Mean	0.139	13	.200*
	80_WE_S_Mean	0.127	13	.200*
Coupling 2	20_WS_S_Mean	0.13	13	.200*
	80_WS_S_Mean	0.112	13	.200*
Coupling 3	20_ES_S_Mean	0.16	13	0.191
	80_ES_S_Mean	0.137	13	.200*
Coupling 4	20_WS_F_Mean	0.131	13	.200*
	80_WS_F_Mean	0.134	13	.200*
Coupling 5	20_ES_T_Mean	0.182	13	0.08
	80_ES_T_Mean	0.113	13	.200*

* This is a lower bound of the true significance
a) Lilliefors Significance Correction

5.2.2. Vector coding

The results for the coordination patterns in non-fatigued and fatigued states are described in table 10. No significant difference was found for joint coordination in the transversal (t(12) = -0.65, p = 0.5) and the frontal planes (t(12)= -0.39, p = 0.7). However, in the sagittal plane, all coordination patterns change from the beginning to the end of the fatiguing hanging task, and a detailed description of the couplings will follow in the next section.

According to Cohen's D-values, there is a large effect (d = 0.80) for coupling 1 (d = 0.96), coupling 2 (d =-1.82), and coupling 3 (d =-1.46). For coupling 4 (d =-0.09) and coupling 5 (d = -0.14), there is a small effect (d = 0.20 for Cohen's D, d = 0.10 for Pearson's r) (Brydges 2019; Pallant 2007).

Table 10: Descriptive data of climbers' upper limb coupling pairs during a fatiguing hanging test on a 20 mm-edge hangboard.

Paired samples statistics and test

Couplings		**Condition**	**Mean ± Std**	**t**	**df**	**p value**
Coupling 1	wrist-elbow (sagittal plane)	Unfatigued	183.78 ± 23.61	4.366	12	< 0.001
		Fatigued	144.77 ± 28.46			
Coupling 2	wrist-shoulder (sagittal plane)	Unfatigued	162.67 ± 21.36	-8.296	12	< 0.001
		Fatigued	213.57 ± 23.87			
Coupling 3	elbow-shoulder (sagittal plane)	Unfatigued	155.42 ± 24.34	-6.548	12	< 0.001
		Fatigued	208.48 ± 25.47			
Coupling 4	wrist-shoulder (frontal plane)	Unfatigued	188.97 ± 24.69	-0.388	12	0.702
		Fatigued	191.97 ± 22.26			
Coupling 5	elbow-shoulder (transversal plane)	Unfatigued	197.96 ± 18.51	-0.65	12	0.524
		Fatigued	201.14 ± 17.90			

* significant difference between fatigued and unfatigued

Coupling 1: wrist-elbow in the sagittal plane

The coupling angles between the wrist and elbow in the sagittal plane decrease from the non-fatiguing to the fatiguing states during hanging (unfatigued: M = 183.78, SD = ± 23.61, fatigued: M = 144.77, SD = ± 28.46; coupling 1: t(12) = 4.366, p = <0.001). The coordination of wrist-elbow coupling in the sagittal plane is depicted in figure 10. When climbers start the hanging, the task was mainly led by wrist extension. Towards the failure, coordination changes to an anti-phase mode between wrist and elbow extension.

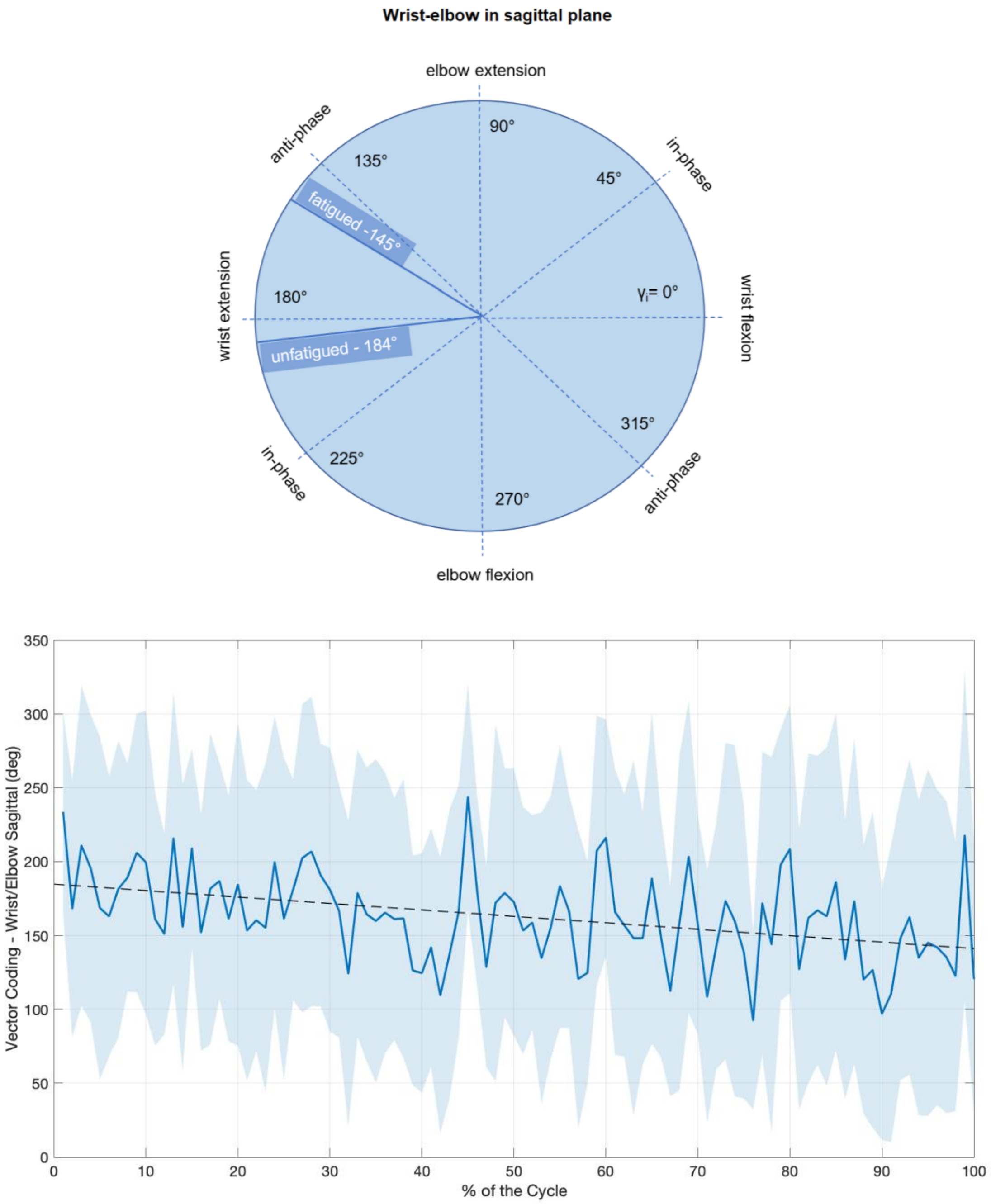

Figure 10: Classification of coordination patterns based on vector coding analysis. Coordination patterns of the wrist-elbow coupling angles in the sagittal plane during a fatiguing hanging task in climbers.

Coupling 2: wrist-shoulder in the sagittal plane

The coupling angles between the wrist and shoulder in the sagittal plane increase from the non-fatiguing to the fatiguing states during hanging (unfatigued: M = 162.67, SD = ± 21.36, fatigued: M = 213.57, SD = ± 23.87; coupling 2: $t(12) = -8.296$, $p = <0.001$). The coordination of wrist-shoulder coupling in the sagittal plane is depicted in figure 11. When climbers start the hanging, the task was led by anti-phase mode but mainly by wrist extension. Towards the failure, coordination changes to an in-phase mode between wrist extension and shoulder flexion, whereas the shoulder becomes the more dominant part.

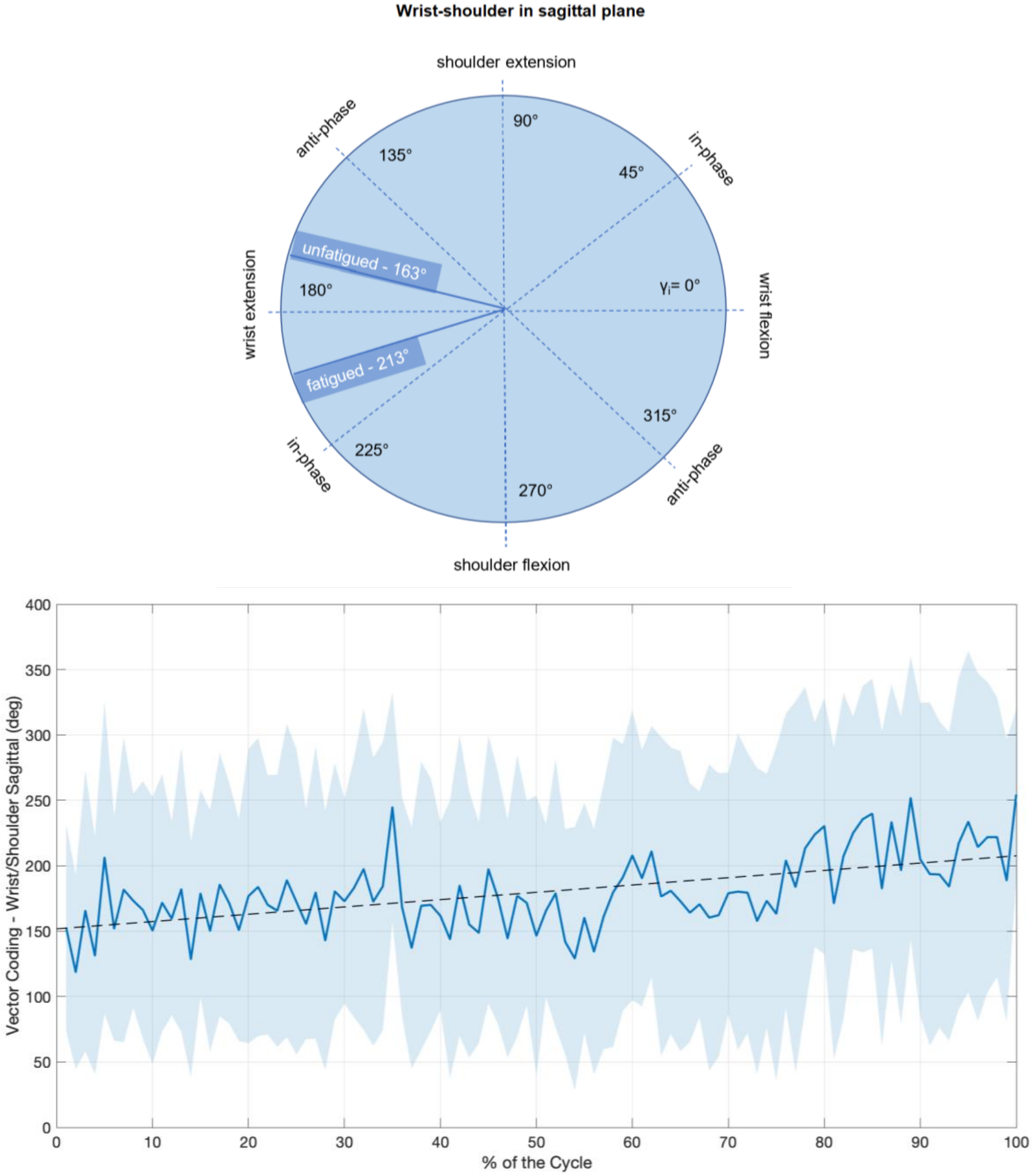

Figure 11: Classification of coordination patterns based on vector coding analysis. Coordination patterns of the wrist-shoulder coupling angles in the sagittal plane during a fatiguing hanging task in climbers

Coupling 3: elbow-shoulder in the sagittal plane

The coupling angles between the elbow and shoulder in the sagittal plane increase from the non-fatiguing to the fatiguing states during hanging (unfatigued: M = 155.42, SD = ± 24.34, fatigued: M = 208.48, SD = ± 25.47; coupling 3: t(12) = -6.548, p = <0.001). The coordination of elbow-shoulder coupling in the sagittal plane is depicted in figure 12. When climbers start the hanging, the task was led by anti-phase. Towards the failure, coordination changes to an in-phase mode between elbow extension and shoulder flexion.

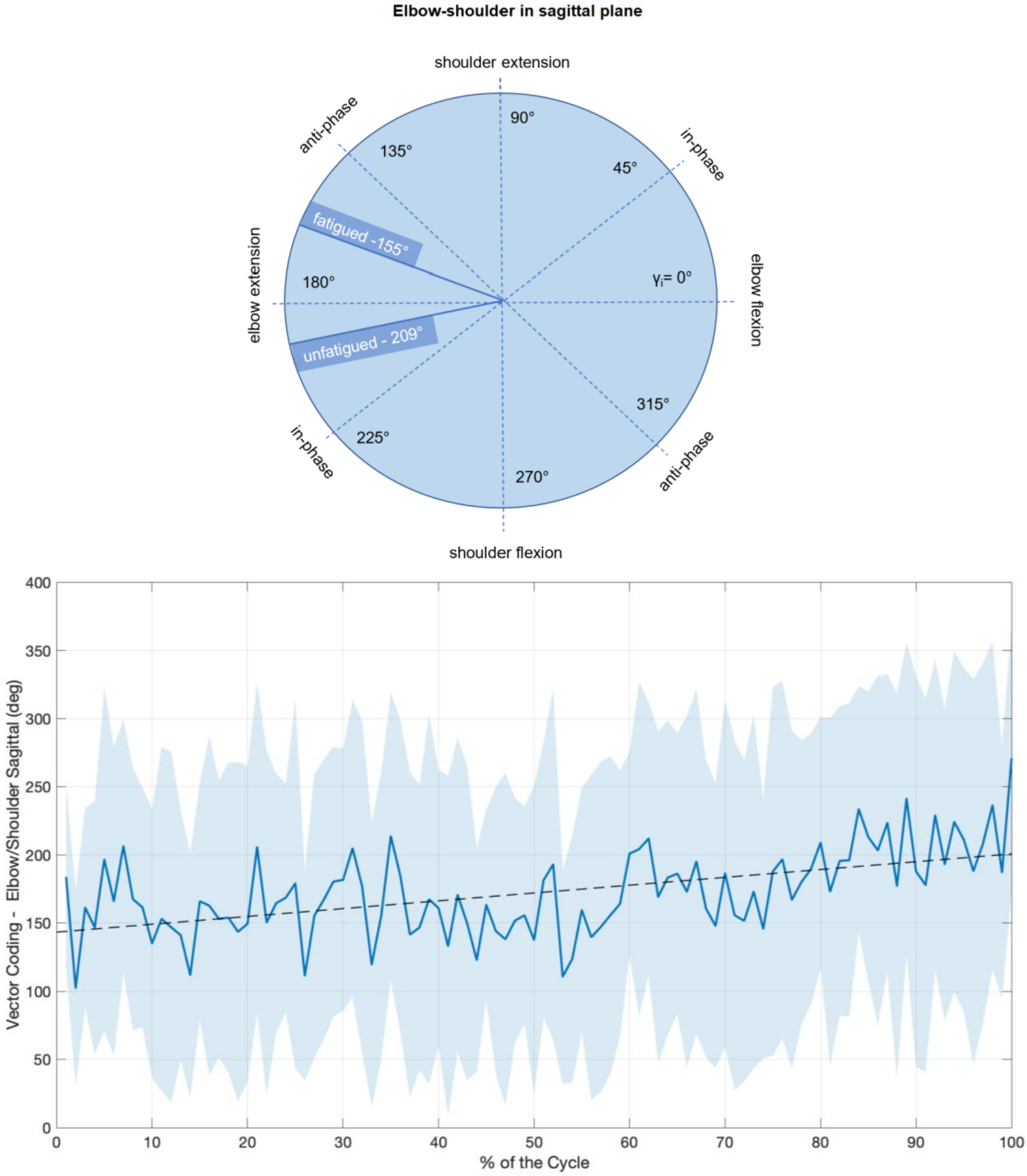

Figure 12: Classification of coordination patterns based on vector coding analysis. Coordination patterns of the elbow-shoulder coupling angles in the sagittal plane during a fatiguing hanging task in climbers

Coupling 4: wrist-shoulder in the frontal plane

The coupling angles between the wrist and shoulder in the frontal plane mostly stagnate from the non-fatiguing to the fatiguing states during hanging (unfatigued: M = 188.97, SD = ± 24.69, fatigued: M = 191.97, SD = ± 22.26; coupling 4: t(12) = -0.388, p = 0.7). The coordination of wrist-shoulder coupling in the frontal plane is depicted in figure 13. When climbers start the hanging, the task was led by wrist ulnar deviation. Towards failure, coordination patterns do not change significantly.

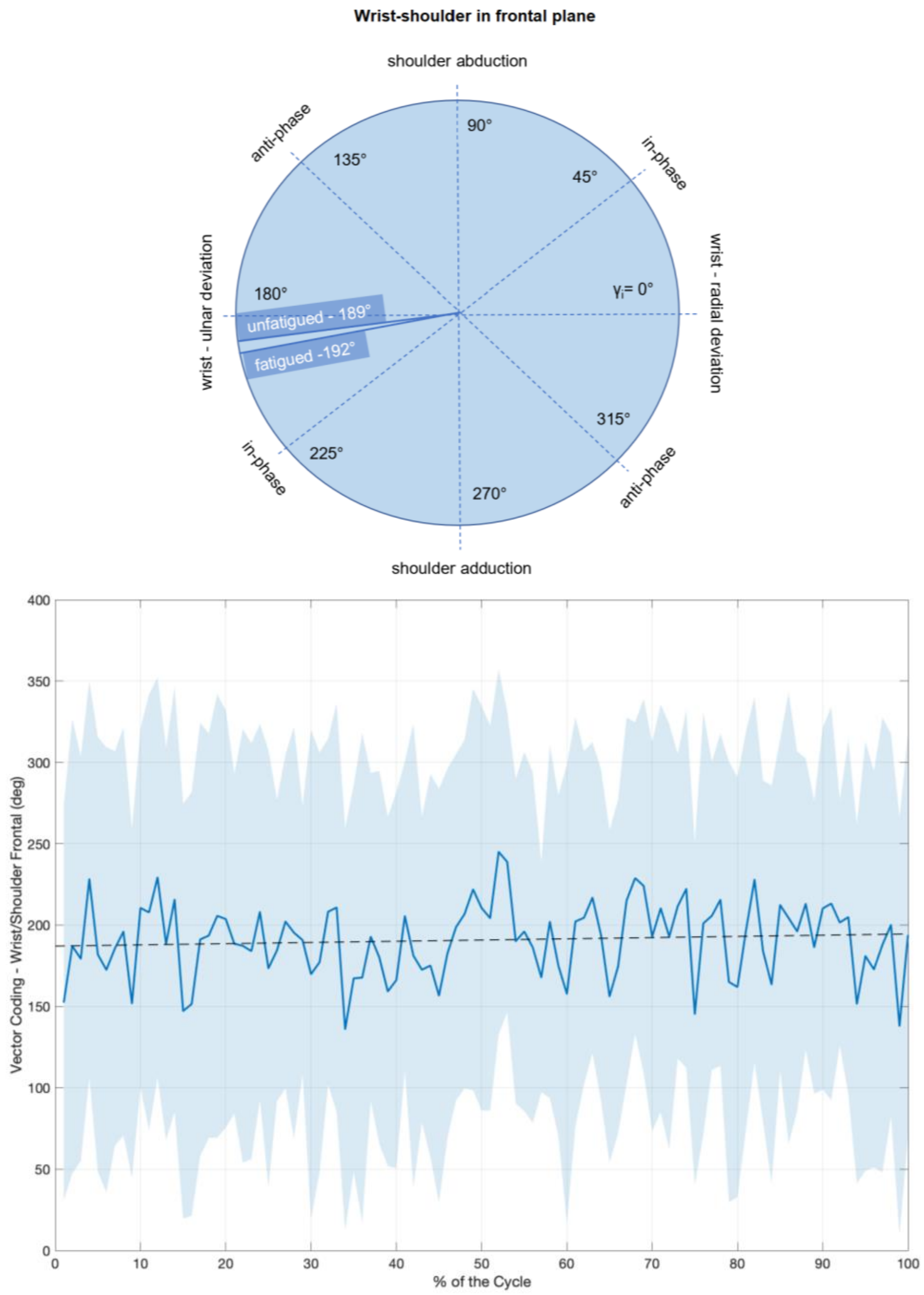

Figure 13: Classification of coordination patterns based on vector coding analysis. Coordination patterns of the wrist-shoulder coupling angles in the frontal plane during a fatiguing hanging task in climbers

Coupling 5: elbow-shoulder in the transversal plane

The coupling angles between the elbow and shoulder in the transversal plane have similar values from the non-fatiguing to the fatiguing states during hanging (unfatigued: M = 197.96, SD = ± 18.51, fatigued: M = 201.14, SD = ± 17.90; coupling 5: $t(12) = -0.65$, $p = 0.5$). The coordination of elbow-shoulder coupling in the transversal plane is depicted in figure 14. When climbers start the hanging, the task was in between the elbow and in-phase with radial deviation and internal rotation. Towards the failure, the mean value is ≈ 201° which is still considered elbow-phase but close to in-phase. The elbow in the transversal plane is in a pronated position due to his radio-ulnar joint (Biel and Dorn 2014). The shoulder movement in the fatigued state tends to be an internal rotation.

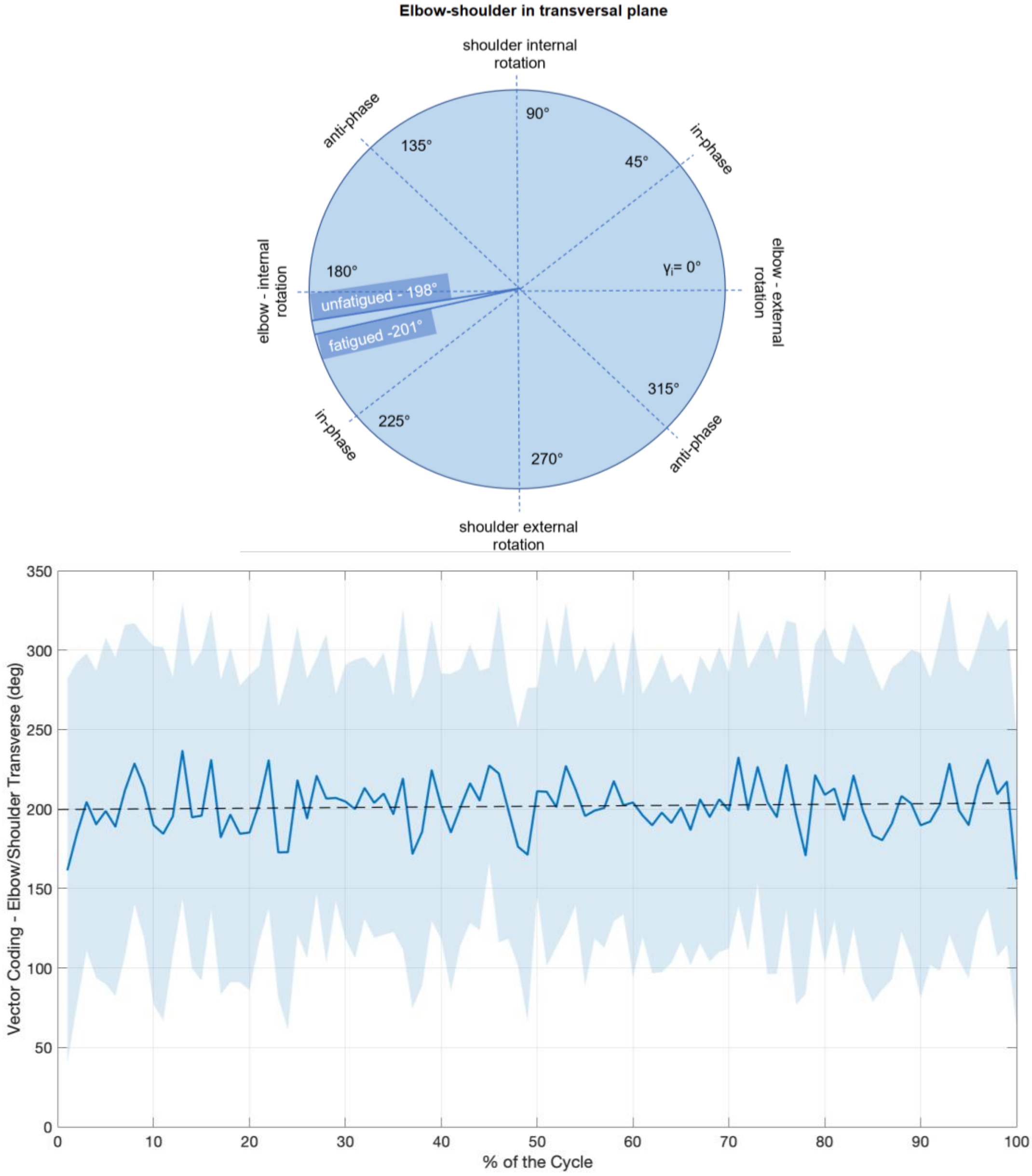

Figure 14: Classification of coordination patterns based on vector coding analysis. Coordination patterns of the elbow-shoulder coupling angles in the transversal plane during a fatiguing hanging task in climbers

6. Discussion

The aim of the present study was to assess and describe climbers' upper body muscle activity as well as the joint coordination strategies during fatiguing finger hangings in climbers. The results showed that coordination patterns of the upper limb change mostly on the sagittal plane towards task failure, and muscle activation of bigger muscles of the upper limb also changes to allow the isometric hanging task. For the RMS, a significant increase in the level of muscle activation and a decrease in the median frequency was found for most studied muscles during the hanging task. These results are corroborated by previously described time and frequency domain EMG variables during fatiguing isometric contractions (Konrad 2006; Merletti and Parker 2004; Quaine et al. 2003).

The control and coordination of movement depend on the initial postural conditions (Testa, Martin and Debû 1999). To start maintaining static equilibrium while supporting their body weight with fingers holding a 20 mm-depth edge, climbers had the wrist-elbow coupling in anti-phase coordination for the sagittal plane motion. This means that in the first 20% of the task, the wrist is being held extended, and the elbow tends to flex. Shoulder-wrist, as well as elbow-shoulder couplings in the sagittal plane, also act in anti-phase coordination. On the frontal plane, the wrist-shoulder coupling is led by wrist ulnar deviation. On the transversal plane, the elbow-shoulder coupling is in between the elbow and in-phase with ulnar deviation and internal rotation. Thus, hanging from the first finger phalanges demands small postural adjustments to compensate for the shift in the body's center-of-mass position as a consequence of perturbations yielded by such a narrow base of support. Although a narrow area of support does not compromise bipedal standing postural stability in some sports (e.g., gymnasts and ice-hockey players), the ability to maintain balance in sport-specific positions might differ from the type of stance (Zemková 2014).

The present study showed that there is an organized displacement of body segments of climbers to maintain the body steady when they start hanging from their fingertips. This can be seen as anticipatory postural adjustments, which should minimize the expected balance perturbation caused by the narrow basis of support and contribute to the hanging efficiency. Such postural adjustments are also accompanied by changes in muscle activity. Thus, the amplitude of the EMG signal shows that muscle activation has a slow increase at the beginning of the task, especially for the finger flexor, finger extensor, and *brachioradialis*. However, towards the failure point of the finger hanging task, typical changes in the upper limb coordination patterns and muscle activation were found. Three couplings showed to significantly change sagittal plane movement from the beginning to the end of the fatiguing task: wrist/elbow, wrist/shoulder, and elbow/shoulder. Around 20% of the fatiguing task, wrist/elbow phase coupling indicates a dominance of the wrist in extension over the elbow, which progresses to an anti-phase relationship with the elbow tending to flex as the wrist maintains or increases extension at the failure point. Wrist/shoulder and elbow/shoulder couplings had similar behavior with time. Results showed that when reaching failure, climbers' wrists and elbows change from an anti-phase coupling with the shoulder, in which joints are extended while the shoulder is flexing, to the domination of the shoulder. Thus, from the present results, it is possible to argue that, with fatigue, the postural adjustments performed by climbers demand higher participation of the shoulder to sustain the hanging. Previous literature has already pointed out interesting factors that influence finger force generation in climbers. Fingers' maximal vertical and antero-posterior forces, i.e., are more associated with the optimization of finger-hold contact and interaction than with internal biomechanical factors, as previously reported (Amca et al. 2012). Interestingly, antero-posterior contact in crimp positions, as used by the present study, is associated with different wrist angles when compared to a slope grip. The authors also found that climbers, when crimping, modified the wrist angle by promoting a higher extension, while when using slope grip, the wrist was more flexed and the arm segment more inclined in relation to the frontal plane. Thus, in a crimp position, climbers would be freer to adjust body posture with the fixed hand to help keep fingers in place and maximize the contact between the fingers and the hold.

Wrist, thus, forearm position is important to yield and hold the proper finger contact in the task. However, when the ability to maintain work is decreasing with fatigue, upper-level joints start playing an important role. In fact, the extended position of the wrist lengthens the finger flexors, favours the action of passive and elastic tissues, and allows for more efficient force production (Li 2002). Thus, it seems that there are specific coordination patterns between the wrist, elbow, and shoulder to compensate for the muscle fatigue effects and maintain the climber in a balanced posture and grip the hold in the most efficient position throughout until failure. The EMG results confirm these compensation strategies at the muscle activation level. Although the degree of activation of the finger flexors did not change with fatigue, the conduction velocity of the muscle fibers decreased, which speaks for the impairment imposed by fatigue. The *brachioradialis* maintains a high activation over the course of the sustained hang, while the *biceps* shows a rapid increase in the end of the task to maintain wrist and elbow at anti-phase coordination. There is also an increase of the *pectoralis major* and *trapezius* in the last 20% of the task, so the shoulder can compensate for the postural adjustments to keep the fingers positioned in the most efficient crimp grip. It is interesting to note the level of co-contraction of the finger muscles shown in this study regarding the hypothesis that there is a migration of muscle activity within synergists and reduction of coactivation within antagonists (Konrad 2006). Although research has reported that coactivation increases when load increases (Psek and Cafarelli 1993), in the present study, finger extensors were active at a very similar intensity as the finger flexors during the task. In literature, such behavior of the finger flexors and extensors can be described with the so-called "common drive", which is based on the hypothesis that the central nervous system controls each motoneuron pool of each muscle with a single input when both muscles are involved in a specific movement (Psek and Cafarelli 1993). Potentially this relationship has the function of relieving ligaments and maintaining joint stability (Psek and Cafarelli 1993). Coactivation refers to the simultaneous activation of agonist and antagonist muscles and therefore provides joint stability. This protective strategy needs to be adjusted continuously by the nervous system in order to ensure that agonist muscle performance is not compromised. Time to task failure can be increased if coactivation decreases during the course of a sustained contraction. This however reduces joint stability and increases susceptibility to injury. On the other hand, an increased coactivation may lead to a loss of force-generating capacity, which is accompanied by fatigue. For this reason, the nervous system must continuously adjust coactivation during a contraction to ensure both optimal performance and stability (Lévénez et al. 2005).

The results obtained in this thesis contribute additional information on the topic once they are the first to describe such joint coordination strategies and muscle activation during isometric and sustained finger hangings.

7. Limitations

Although the present thesis could reveal coordination and muscle activation patterns of climbers under a fatiguing finger hanging, the study has some limitations. The task consisted of a continuous sustained isometric contraction of the finger flexors until failure. Climbing is an activity characterized by intermittent bouts of isometric contractions. Thus, an intermittent protocol could present a higher degree of ecological validity with sport/activity performance. However, the repeated re-positioning of the fingers in the hold of the hangboard could change the whole-body kinematics and add other limitations to the interpretation of the data. The preference for a sustained contraction fitted better the purpose of understanding joint coordination and compensation strategies elicited by fatiguing state.

One fact which should be addressed is the lack of force measurements. Fatigue describes the reduced capacity to maintain work. Thus, while performing sustained hangings by the fingers until failure, there is a loss of grip strength which leads to a decrease in contact force (Watts et al. 2008). It would be interesting to understand, with the changes in joint coordination and muscle activation, the rate and behavior of the loss in contact forces caused by fatigue. Also, such changes as the function of limb laterality would complement to the understanding of possible side imbalances and their influence on joint coordination during fatiguing tasks.

8. Conclusion

In order to understand how muscle activity and coordination patterns behave in climbers who perform fatiguing finger hangings and use other parts of their body to hold the specific position asked for, kinematic and sEMG data from healthy climbers was collected and analyzed.

The greatest changes relating to joint coordination were seen in the sagittal plane, with the wrist extension proving to be dominant in the unfatigued state, which is consistent with the literature and should ensure that the climber can move more freely and thus change their posture with the fixed hand to help keep fingers in the right place and maximize the finger-hold contact (Amca et al. 2012; Li 2002). In the fatigued state, upper limbs get more involved, whereas in the sagittal plane, dominance shifts to elbow and shoulder flexion. That can also be seen in upper limb muscle activation e.g., shoulder and chest musculature supporting the finger flexors at the end of the task to remain in the body position. In the frontal plane, the wrist was dominant, with ulnar deviation throughout the whole hanging. No changes were investigated in the transversal plane, where the elbow was the dominant segment with internal rotation and ulnar deviation the whole trial.

In summary, muscle activation under fatiguing conditions agreed with the literature, with RMS showing an increase and MF decreasing for most upper limb muscles (Konrad 2006; Merletti and Parker 2004). *Trapezius* and *pectoralis major* showed a different behavior, which corresponds to joint coordination data that in the fatigued state, upper-level joints and limbs such as the shoulder are starting to play an important role. Since the co-activation of the antagonists of the finger flexors was about equally the same, this strategy could be invoked to relieve ligaments and ensure joint stability.

All in all, sEMG and kinematic results show that there is an organized displacement of body segments of climbers to maintain the body position asked for, whereas the postural adjustments were accompanied by muscular activity. As this thesis dealt mostly with motor control of sustained finger hanging, understanding the neuromechanics behind sustained contractions is important. Enlightenment may be found in anticipatory postural adjustments as they lead to more efficient movements by minimizing expected balance perturbations.

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10. Tables

11. Figures