Glove effects on forearm muscle activity in a windsurfing-like task

MSc thesis N.M. Mulders
Glove effects on forearm muscle activity in a windsurfing-like task

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Glove effects on forearm muscle activity in a windsurfing-like task


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Abstract: Windsurfers currently do not wear neoprene gloves when sailing in cold temperatures, as discomfort rapidly develops in the forearms when doing so. Lack of good protection against low temperatures means the hands get painfully cold and numb, limiting sailing time and pleasure. ElectroMyoGraphy (EMG) measurements were done on four forearm muscles of 10 healthy, experienced male windsurfers performing a windsurfing-like task, to find differences in muscle activation between the bare hand, two glove types, and a newly developed experimental prototype. Significantly less EMG activity was associated with the prototype condition for three out of four muscles, compared to the bare hand and glove conditions. No significant differences in muscle activation were found between the bare hand and the two glove conditions. Results of a questionnaire revealed that subjects found both glove conditions significantly more tiring than the bare hand and prototype conditions. The EMG measurement results indicate that the experimental prototype allows sailors to transfer forces between arm and boom with less effort than in bare hand or gloved conditions, but a probable cause of the forearm discomfort when wearing gloves was not found.

Keywords: Glove, windsurfing, electromyography, EMG.

1 Introduction

1.1 Background

As air flows across the sail (Fig. 1, item 1), an aerodynamic lift force is generated, driving the windsurfer across the water. To maintain the sail’s position, the sailor (Fig. 1, item 5) uses his body weight to counteract the sail’s pulling force. The sail force is transferred to the sailor through mast and boom (Fig. 1, item 2 & 3). Most of the time, a large portion of that force is transferred through the harness lines and harness (Fig. 1, item 6 & 7). The harness is worn around the waist. By transferring the force through the harness, the arms are relieved, reducing the rate of fatigue in the shoulders, arms and hands. A downside of using the harness is that the range of motion of the sail relative to the sailor’s body is reduced. In rough water or with gusty winds, a large range of motion allows sailors to make corrections to the sail position and angles and prevent falls, so the harness is unhooked. Also, to perform maneuvers such as jibing, tacking and jumping, sailors generally unhook the harness.

Figure 1: The main components in a windsurfing rig. 1 Sail, 2 Mast, 3 Boom, 4 Board, 5 Sailor, 6 Harness, 7 Harness lines. (Image courtesy of G. Cammarota)
When the harness is unhooked, sailors hold the boom with their hands. To be able to transfer the force between sail and body with the harness unhooked, muscles in the forearm must flex the fingers around the boom to grip and hold the boom. With the harness engaged, a force of roughly half the body weight is transferred through the harness lines[19]. Although transferring a force of such magnitude through the arms is physically demanding, it is sustainable for short periods of time in normal conditions. However, problems arise in late autumn and winter when temperatures decrease.

1.2 Problem statement

As modern wetsuits become increasingly capable of maintaining body temperatures at a comfortable level, people can windsurf for longer periods of time, and for increasingly larger portions of winter seasons in cold climates, such as in northern Europe. Neoprene hoods and boots are worn to reduce heat loss from the head and feet. Currently, the first body parts that get cold are the hands, due to a lack of good protection from the cold air and water. Neoprene gloves exist, however they are currently not used for windsurfing, as sailors who wear these gloves experience a rapid onset of discomfort in the forearms. Literature describes several glove effects on grip force:

- Due to their stiffness, gloves typically form a resistive factor against bending of the fingers. As the bending stiffness of the hand and glove combined is higher then the bending stiffness of just the bare hand, more muscle force must be generated to exert the same external grip force, when gloves are worn.[11, 20]. To increase the generated muscle force, muscle activation must be increased.
- Gloves reduce tactile feedback. A reduction of tactile feedback tends to cause an increase in applied grip force and thus higher muscle activations in sub-maximal grip tasks.[3, 8, 9, 20]
- A reduced coefficient of friction results in a lower breakaway force, or maximal pulling force, as a smaller portion of the total pulling force can be transferred by friction between hand and handhold.[7, 22, 23]
- The glove thickness increases the effective gripped diameter. Maximum grip force is dependent on diameter[5, 6]. As there is an optimum diameter, increasing the diameter could both increase or decrease maximum grip force, depending on whether the object’s diameter is higher or lower than the optimum diameter.

Currently, there is a gap in the literature on the effects of gloves on sub-maximal pulling tasks in general. As windsurfing is an activity where gloves apparently negatively affect the sailor’s task endurance, a study was set up to find glove effects in a windsurfing-like task, and to simultaneously study the effects of two potential solutions to the discomfort problem.

A possible cause of the discomfort felt in the forearms when wearing gloves is muscle fatigue, as a result of elevated muscle activation levels. Muscle activation can be measured using (surface) EMG, in which muscle activation pulses are measured using electrodes on the skin. Increased muscle activation is associated with an increase in generated muscle force[2]. An increase in muscle force in turn results in a higher rate of fatigue.

The first potential solution is to use a low stiffness glove, which is a regular glove that is modified such that its resistance to bending is reduced. As glove stiffness is reported to be one of the main causes of reduced glove performance[11, 20], such a glove could be also be a simple solution to the problem.

A second potential solution is wearing a forearm brace in combination with gloves, that is able to transfer all, or part of, the pulling force from the boom to the forearms. By reducing the level of required muscle activation in the forearm, such a brace could decrease the discomfort experienced by glove wearing windsurfers. The brace would allow sailors to wear gloves, and thus keep their hands warm.

1.3 Hypotheses

To evaluate the effect of the proposed solutions, three hypotheses were formulated:
H1. When wearing regular neoprene gloves, people exhibit significantly higher average forearm muscle activation, compared to the bare hand.

H2. When wearing the low stiffness gloves, people exhibit significantly lower average forearm muscle activation, compared to the regular gloves.

H3. When using the brace, people exhibit significantly lower average forearm muscle activation compared to the bare hand or glove.

2 Materials and methods

2.1 Subjects

Ten healthy, experienced male windsurfers participated in the experiment (App. G & Table 1). When asked, no subjects reported any medical conditions that negatively affect the use of the right arm or hand. All subjects gave informed consent and signed a consent form (App. J) prior to participation in the experiment. The research was approved by the Human Research Ethical Committee (HREC) of TU Delft (App. U).

<table>
<thead>
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<th></th>
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<tr>
<td>Middle finger length [cm]</td>
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Table 1: Subject demographic with means and standard deviations

2.2 Experimental set-up

The experiment took place at Delft University of Technology’s Mechanical Engineering faculty in Delft, The Netherlands. A hydraulic actuator[16](Fig. 2, item 7), in combination with pre-tensioned springs (supplied by Roveron, Rotterdam, The Netherlands), provided pulling force to a horizontally mounted crossbar (Fig. 2, item 2). The sum of spring force $F_{spring}(t)$ and actuator force $F_{ref}(t)$ was transferred to the handhold (Fig. 2, middle-right). Software limited the actuator’s reference force between -130 and 180 N, to protect the actuator’s hardware. The subjects pre-tensioned the springs to allow a higher maximum handhold force $F_{handhold}(t)$. The target position was defined as the crossbar location where the $F_{spring}(t)$ was 125 N. The handhold (Fig. 2, item 1) was designed to allow subjects to hold a piece of genuine boom material and was attached to the actuator by a cable (Fig. 2, item 4). Details of the handhold and setup can be found in Appendix A. The 1.5 m long cable between handhold and actuator allowed the subject to always remain outside the actuator’s range of motion. The cable also acted as electrical insulation between actuator and subject. Additionally, to protect the subject, in the unlikely case that software safety precautions failed and an excessive tensile load was exerted on the handhold and subject, a magnetic coupling was installed in the cable and calibrated to release at a tensile load of 370 N (App. B & N, Fig. 2, item 3). The experiment’s intended pulling force $F_{pull}(t)$ was pre-determined and consisted of a bias (average pulling force), and the modeled effects of two sources of disturbances that are encountered in windsurfing: wind speed fluctuations and vertical accelerations due to waves (Fig. 3, App. D). The bias was a quarter of the body weight[19]. The (horizontal) pulling force fluctuations as a result of the windsurfer’s vertical accelerations due to waves and fluctuations in wind velocity were modeled as disturbances. Common windsurfing conditions in the Netherlands were used as a basis to estimate the magnitudes and frequencies of the disturbances. The pulling force was linearly scaled to each subject’s body weight, as the modeled magnitudes of the bias and disturbances forces were linearly dependent on body weight (Fig 4). The force on the actuator was recorded using a force sensor between the actuator’s piston and crossbar. The piston’s position, and thus by extension the crossbar’s position, was recorded using a position sensor within the actuator. Software used the actuator’s position sensor as feedback to calculate the appropriate reference force in real-time, to correct for position errors $p_e(t)$ as a result of
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Figure 2: Subject body position and experiment hardware. ① Handhold, ② Crossbar, ③ Magnetic coupling, ④ Cable between handhold and crossbar, ⑤ Cable to springs, ⑥ Visual feedback monitor and ⑦ Hydraulic actuator

Figure 3: Force signal bias and disturbance for an 80 kg subject

spring force differences (Fig 4). By doing so, the force signal was the same during each trial, independent of handhold position differences. Because the force profile was the same in each trial, muscle activity differences could be compared between conditions. The force and position sensor readings were captured and A/D converted

Figure 4: Block diagram showing how the controller used several inputs, constants and variables to calculate the force $F_{ref}$ the actuator should apply. The "disturbance blocks" contain look-up tables for a 80kg subject. Their output is subsequently scaled to the current subject’s body weight

at a sampling rate of 1000 Hz. Delsys DE-2.1 electrodes recorded EMG signals of the Flexor Digitorum Superficialis (FDS), Extensor Digito-
2 MATERIALS AND METHODS

rum (ED), Extensor Carpi Radialis (ECR), and Flexor Carpi Radialis (FCR) (Fig. 5). EMG signals were amplified by a Bagnoli desktop amplifier with a bandpass filter of 20 - 450 Hz. EMG signals were captured and A/D converted at a sampling rate of 1000 Hz.

Figure 5: Electrode placement on a subject (top). Anterior (middle) and posterior (bottom) view of model of the right forearm. 1 FDS, 2 ED, 3 ECR, 4 FCR and 5 Reference electrode

2.3 Task instruction

Subjects were instructed to maintain the handhold near the target position and to relax their body as much as possible, without letting the handhold slip from the grip of their right hand. A monitor (Fig. 2, item 6) in front of the subjects displayed the target position and current handhold position. Subjects knelt on a 50 mm thick self-inflating air mattress on the floor with both knees, facing the actuator, in such a way that their right arm was fully extended and in line with the actuator’s stroke (Fig. 2). The mattress allowed subjects to kneel more comfortably, and would cushion any potential falls.

The subject’s position on the floor was such that they could lean backward with the arm extended to pretension the springs. The task instruction was assumed to result in a grip on the handhold which is as representative as possible for the grip on a windsurfing boom during sailing, as far as the muscles in the hand and forearm were concerned.

2.4 Experiment procedure

To calibrate the spring system, the hydraulic actuator was pushed out until the force in the springs was 125 N, measured using the actuator’s force sensor. Calibration was done with the handhold cable slackened. The equilibrium position was stored as the target position. Four conditions were tested; bare hand, glove, low stiffness glove (LSglove)(Fig. 6) and an experimental prototype (Fig. 7). The glove was a

Figure 6: The bare hand (top left) and glove condition (top right). LSglove shown in bottom row.

3 mm thick O’neill Psycho neoprene surf glove. The glove was obtained from Siem de Jong Fun-sports, Delft, The Netherlands. The LSglove was equal to the glove, except the topside was cut open, at the location of the metacarpophalangeal (knuckle) and interphalangeal (finger) joints, to reduce the glove’s stiffness to bending. The final condition; the newly developed Prototype was worn on the forearm in combination with the regular glove and a neoprene sleeve (Fig. 7 &
A nylon strap looped around the handhold and was adjusted to the appropriate length for a natural grip posture of the hand, using a buckle. The strap allowed subjects to partially transfer the pulling force from handhold to the lower arm, relieving the hand and fingers. Before the actual experiment, subjects performed a training trial with each condition to familiarize themselves with the conditions and the experiment. Each condition was repeated 3 times per subject, and the condition order was randomized using MATLAB, for each repetition and subject (App. G). To ensure a realistic coefficient of friction between the hand and handhold, the subject’s hand (or glove) and the handhold surface were wetted with seawater, prior to each trial. When the subject was in the correct position, equipped with the correct glove condition, and verbally communicated that he was ready for the trial, the researcher started the experiment. The subject resisted the pulling force on the handhold for 46 seconds. Of those 46 seconds, 5 seconds were used to slowly increase the actuator’s force to the appropriate level. The seemingly strange 41 remaining seconds were needed have the sinusoidal wave disturbance end around 0 N.

After the third repetition of each condition, subjects filled out forms (App. K), in which they visually marked how tiring each condition was, in their personal experience. Each form contained a 10 cm long horizontal line without a scale or any other markings. Before the experiment, subjects were unaware of the existence of these forms, and while marking these forms, any forms they had marked earlier were kept out of sight.

2.5 Data processing and statistics

2.5.1 EMG data

The EMG data, each consisting of 46000 data points, were first filtered using a discrete Fourier transform to exclude electrical interference from the building’s 50 Hz electrical mains into the EMG data, which would contain a 50 Hz component and its higher harmonics. Subsequently, a second order non-causal high-pass Butterworth filter was applied with a cut-off frequency of 20 Hz, using the lower cut-off frequency of the main amplifier’s bandpass filter of 20 - 450 Hz. The signal was then rectified by taking the absolute value of each datapoint. Finally, a second order non-causal low-pass Butterworth filter was applied with a cut-off frequency of 3 Hz[14] (App. H). After filtering, the first 5 seconds of each signal was removed. The mean value of the remaining 41 seconds was used as a metric for muscle activity during the experiment. During electrode placement, subject seven’s ECR electrode pre-amplification was set at 10k, as the signal was weak. Data from that muscle were scaled to match all other subjects’ 1k pre-amplification level (App. G). The mean value of the three repetitions of the same muscle and condition were used for the statistical tests. As the EMG data were not normally distributed, which was tested with a Shapiro-Wilk and Kolmogorov-Smirnov test, Wilcoxon signed rank tests were performed to correct for inter-subject differences. A Bonferroni correction was applied to correct for testing between all four conditions (6 tests), meaning that significance level \( \alpha \) was adjusted to \( \alpha = 0.05/6 = 0.0083 \).

2.5.2 Estimation of fatigue rate

The length of the horizontal line left of the subject’s mark on the fatigue estimation forms was taken as the metric to process. The data acquired from these lengths were verified to be normally distributed, using Shapiro-Wilk and Kolmogorov-Smirnov tests. To correct for inter-subject differences in interpretation of forms,
3 RESULTS

3.1 EMG data

Subjects showed peaks in EMG activity corresponding to peaks in the force signal (Fig. 3, 8 & 10 (top)). This behaviour was observed in the readings of all four muscles. Typically, the finger flexor (FDS) showed the highest (absolute) EMG activity, followed by the wrist flexor (FCR) (Fig. 10). All subjects showed low finger and wrist extensor (ED, ECR) activity. Inter-subject variability was large, with standard deviations often in excess of half the mean. The EMG measurement data did not test positive for normality. Post-hoc testing revealed a significant decrease in average muscle activation for the Prototype condition compared to the bare hand, glove and LSglove conditions for the FDS, ECR and ED muscles, but not the FCR (Fig. 10). No other significant differences were found between conditions in any muscle.

3.2 Fatigue rate questionnaire

The results of the questionnaire regarding estimated fatigue rates between conditions are shown in Fig 9. The Bare hand condition’s estimated rate of fatigue was significantly lower than the Glove condition’s and the LSglove condition’s, but did not differ significantly from the Prototype condition. The Prototype was rated significantly lower than the Glove condition and the LSglove condition. Glove and LSglove conditions were not rated significantly different.

Figure 8: A typical filtered EMG signal. (Data from subject 5’s FDS muscle, during the third repetition of the LSglove)

Figure 9: Boxplot of the estimated rates of fatigue of the various conditions including the medians (red), 25th-75th percentile (blue) and the minimums and maximums (black). Outliers are shown as red plusses. Statistically different conditions for one muscle are denoted by different letters (a or b)

paired dependent T-tests were done. A Bonferroni correction was applied to correct for testing between all four conditions (6 tests), meaning that significance level $\alpha$ was adjusted to $\alpha = 0.05/6 = 0.0085$. 
Figure 10: Top: Mean filtered EMG data of all subjects. Bottom: Boxplot of EMG measurement data of all conditions and muscles showing the medians (red), 25th-75th percentile (blue) and the minimums and maximums (black). Outliers are shown as red plusses. Statistically different conditions for one muscle are denoted by different letters (a or b).
4 Discussion

4.1 Hypotheses

A recap of the hypotheses as formulated in the Introduction:

**H1.** When wearing regular neoprene gloves, people exhibit significantly higher average forearm muscle activation, compared to the bare hand.

**H2.** When wearing the low stiffness gloves, people exhibit significantly lower average forearm muscle activation, compared to the regular gloves.

**H3.** When using the brace, people exhibit significantly lower average forearm muscle activation compared to the bare hand or glove.

**H1: Glove effects**

Even though the mean wrist flexor (FCR) activity was 12% higher for the glove condition (mean = 0.0566 V, SD = 0.0236 V) than the bare hand condition (mean = 0.0505 V, SD = 0.0237 V), large intra-subject variability made the difference not statistically significant. The finger flexor (FDS) was the muscle with the highest absolute activity during the experiment, but no significant differences were measured between bare hand (mean = 0.0798 V, SD = 0.0448 V) and glove conditions (mean = 0.0831 V, SD = 0.0412 V). The wrist and finger extensors (ECR and ED) measurements were not significantly different either between glove and bare hand conditions. Based on the lack of significant differences between the bare hand and the glove conditions, the first hypothesis H1 must be rejected.

**H2: LSGlove effects**

There were no significant differences in muscle activity for any muscle between the glove and LSGlove conditions. Differences were expected mainly for the FDS muscle, as a reduced stiffness to bending would primarily affect FDS activation. However, the differences in FDS activation between Glove and LSGlove conditions (mean = 0.0783 V, SD = 0.0399 V) were minimal and not statistically different. Consequently, the second hypothesis H2 must also be rejected.

**H3: Prototype effects**

Subjects appeared to use the prototype’s ability to transfer part of the pulling force. Consequently, finger flexor (FDS) muscle activation with the Prototype (mean = 0.0369 V, SD = 0.0153 V) was significantly lower than with Bare hand and Glove conditions, with on average 54% and 56% less muscle activation, respectively.

Both wrist and finger extensors (ECR and ED) showed significantly less muscle activity in the Prototype condition than in Bare hand and Glove conditions. For the ED, muscle activation with the Prototype condition was 48% and 51% less than the Bare hand and Glove conditions, respectively. For the ECR, muscle activation with the Prototype condition was 73% and 76% less than the Bare hand and Glove conditions, respectively.

Although the FCR on average exhibited 21% and 30% less muscle activity with the Prototype than with the Bare hand and Glove conditions, respectively, FCR muscle activation was not statistically different for any condition. Because not all forearm muscles were measured and the FCR was not significantly less active, the hypothesis cannot directly be accepted. However, the results do seem to indicate that wearing the prototype allows people to transfer the same pulling force with less effort. That is also indicated by the questionnaire’s results.

4.2 Muscle recruitment

The finger flexor (FDS) showed the highest absolute activity. This was not surprising as the FDS is primarily flexes the fingers[15], which is necessary to place the fingers around the handhold and resist the pulling force. The finger extensor (ED) showed very little activity throughout the experiment for all subjects, indicating that holding the handhold was not done by increasing the interphalangeal joint stiffness through co-contraction. Because the FDS is secondarily
also a wrist flexor[15], in a power grip task, the wrist extensors are normally also activated when FDS activity is increased, in order to stabilise the wrist joint[18]. However, this behaviour was not seen in the experiment, which can be explained by the type of task that was performed. Stabilising the wrist is not as necessary in a (submaximal) pulling task as in a pure grip task, as the direction of the pulling force itself acts to stabilise the wrist joint. That is in accordance with the reduced wrist extensor activity Elk et al.[18] reported when an external wrist extension force was applied to the hand.

4.3 Task in experiment vs real life task

The force in the experiment was modeled using a bias, and the effects of two disturbances. In real windsurfing, the sailor needs to adjust his sail angle in order to stay upright. This causes additional force 'disturbances' which were not modeled in the experiment, so the effects of these additional disturbances could play a role in the difference between bare hand and glove conditions.

4.4 FDS EMG-electrode placement

Placement of the FDS muscle EMG-electrode proved difficult, sometimes requiring several replacements of the electrode. Due to the anatomical proximity of the FDS to the adjacent Pollus Longus and Flexor Carpi Ulnaris muscles[15], it is possible that some muscle activity from those muscles was also measured in some subject’s FDS recordings. The FDS muscle fans out into four tendons, each of which inserts into the intermediate phalanges of the fingers[15]. The part of the FDS nearest to the skin flexes the little finger, while the part of the muscle that flexes the other fingers lies deeper below the skin, so that muscle activity controlling those fingers cannot directly be measured using surface EMG. The force contribution of the little finger to the total force in a power grip task is only 12 - 15%[12, 13], so in a pulling task it is likely that the force through the little finger is a a small amount of the total, in which case the results of the FDS measurement could be different if one was able to measure the parts of the FDS that flex the middle-, index- and ringfingers.

4.5 Measured muscles

Not all muscles are measurable using surface EMG, so a selection of muscles to measure was made to include a wide range of muscles that The FDS and ECR were considered good candidates as their activation is associated with gripping[15, 18]. The FCR and ED are antagonists of the ECR and the FDS[15], respectively. The combination of a finger flexor (FDS) and extensor (ED), and a wrist flexor (FCR) and extensor (ECR), meant that muscles for wrist and finger flexion and extension were measured. That meant the measurements could provide insight about those four motions of the hand and wrist and about the possible occurrence of co-contraction. Only four muscles were measured, so there was always the possibility that one of the many other muscles in the lower arm could fatigue more rapidly as a result of wearing gloves. Measuring muscles deeper below the skin is possible using intramuscular-EMG, however this was beyond the scope of this research.

4.6 Increase of diameter

Gloves increase the effective grasped diameter. Possibly, this causes an increase in Flexor Digitorum Profundus (FDP) muscle activation, the muscle that insert into the distal phalanges[15] and primarily flexes the distal interphalangeal joint. Willms et al.[20] measured a decrease in FDS muscle activation when wearing gloves in a maximum grip force task, while other forearm muscles had similar force. It was thought that because the effective grip size was increased, an increased portion of the grip force was supplied by the FDP instead of the FDS. This could play a role in glove wearing windsurfers. FDP muscle activation cannot be measured using surface EMG, as the FDP lies beneath other muscles[15]. Because the goal was to find differences in muscle activity between various conditions, diameter
4 DISCUSSION

differences were not corrected for when gloves were worn.

4.7 Hardware limitations

Pre-tensioned springs were used to increase maximum pulling force, as the actuator force was limited to 180 N. As a result, this required that the handhold be kept near the target position, to be able to exert the necessary forces. To find glove effects, subjects were also asked to relax as much as possible without letting go of the handhold, as having subjects focus on maintaining the handhold at the target position would most likely result in co-contraction throughout the body and arm. Having subjects perform two tasks simultaneously is a so-called double task as subjects are asked to perform two tasks at the same time. A disadvantage of double tasks is that differences can occur between subjects on how much they focused on each task, which means that performing a position task can result in different muscle activation patterns than performing a force task [4]. Each subject was told multiple times, both in writing and verbally, that the most important task was to relax, and that they only needed to stay near the target position due to the set-up’s hardware limitations. The potential occurrence of a double task could have been prevented by fixating the subject’s body position, so that he could focus solely on muscle relaxation. This idea was considered but abandoned, as the body fixation was considered unsafe.

4.8 Body position

Subjects were kneeling down and only held the handhold with one arm. This is a different body position than employed during windsurfing, where sailors stand on their feet and hold the boom with both hands. The experiment design required subjects to experience the same force profile during each trial. If the same force is to be experienced, and the subject must also keep the handhold near the target position, he needs to be able shift his weight backwards and forwards to remain in the same position. When kneeling, subjects had the ability to shift their weight between their feet and knees, allowing them to maintain their position with the various force levels. Had the subject been standing with his feet side by side facing the actuator, he would have had much less possibility of shifting his weight to properly respond to the various force levels. Only one hand was used in the experiment, because of the actuator’s force limitations and required pulling force levels. The way the forearm muscles would behave in transferring pulling force should however not have been affected by the body position, as the hand on the boom was held in a similar way, and the shoulder joint was at similar angle to the core, although this was not controlled for.

4.9 Subject questionnaire

All subjects rated the glove condition as more tiring than the bare hand condition, and all but one rated the LSglove condition as more tiring than the bare hand condition. These differences were statistically significant. As the subjects were all experienced windsurfers and, when asked after the experiments, verbally stated that they have at some point tried windsurfing while wearing gloves, it is possible that they had preconceptions about the various conditions. Those preconceptions could have affected the questionnaire’s results, in which case the difference in outcome between both glove conditions and the bare hand would be based on their windsurfing experience rather than differences in the experiment. As the prototype was an unknown condition, it is promising for its design that subjects on average rated it significantly less tiring than both the Glove and LSglove conditions. It was on average rated as less tiring than the bare hand condition, however the difference was not significant.

4.10 Prototype performance

During the experiment, the prototype functioned well. Subjects only received one training trial with the prototype but quickly understood that they could reduce FDS muscle activation and still transfer the required pulling force. No slip-
ping was noticed between prototype and forearm, although that was not measured. As subjects were explicitly instructed that the prototype should not feel uncomfortably tight, or like it might block blood flow to the hands, the fact that no slipping was noticed reinforces the idea that this way of attaching a brace to the arm is viable. Looping the strap around the boom and through the buckle proved a bit cumbersome, however its adjustability was also necessary, as subjects often requested very small adjustments to get the grip posture just right. For future design, this adjustability should definitely be taken into account. When the strap was too tight, the wrist needed to flex to hold the boom, creating an unnatural hand posture, but when it was too loose, the pulling force was exerted more distally on the fingers, which is not a comfortable hand position to transfer force. A strap that must be looped around the boom using the other hand is not a viable option for real life windsurfing, as it is impractical and time-consuming. The essence of the prototype, the ability to transfer pulling force directly from the boom to the forearm, should definitely be considered when designing a brace for windsurfers.

4.11 General thoughts

In the experiments, the FDS exhibited the highest muscle activity, however there were no differences between Glove and Bare hand conditions. As the FDS is only one of the two main finger flexors[15], it would be interesting to investigate muscle activation of the other main finger flexor, the FDP. This would be especially interesting as the FDP is the only forearm muscle that flexes the distal phalanges[15], which, when gripping a 30 mm cylindrical objects, exert 37% of the total normal force[10], where the middle and proximal phalanges only exerted 24% and 19% of the total force, respectively. FDP activation could unfortunately not be measured with surface EMG as the FDP lies beneath other forearm muscles. In the author’s opinion, the FDP muscle is in hindsight the most likely muscle to fatigue more rapidly as a result of wearing gloves when windsurfing, and should be considered in future research on the subject.

5 Conclusions and recommendations

Conclusions:

- The EMG measurements from the experiment cannot explain the rapid onset of forearm discomfort experienced by glove-wearing windsurfers.
- The EMG measurements from the prototype condition indicate that forearm muscle activity is generally lower with the prototype than when with gloves or the bare hand.
- The cuts in the LSglove did not affect muscle activation, compared to the bare hand.
- Although the muscle(s) responsible for the rapid onset of forearm discomfort in glove-wearing windsurfers were not identified, the significant reductions in muscle activity for 3 out of 4 muscles and the questionnaire results do indicate that a forearm brace in combination with a glove could be used to transfer forces experienced during windsurfing with less effort than when bare-handed, or while wearing gloves.
- The results from the questionnaire indicate that both glove and LSglove conditions felt more tiring than both the Bare hand and Prototype conditions.
- The low muscle activations measured in the ED muscle for all subjects indicate that it was not important for transferring the force in the experiment.

Recommendations:

- Any attempts to design a windsurfing forearm brace to transfer force from boom to forearm should allow adjustability of the length of the force-transferring component.
- In spite of attempts to minimize blood flow restriction, it cannot be disregarded, as excessive restriction might even cause cold and/or numb hands more rapidly, even though gloves are worn. Further research
should attempt to identify and quantify the effect of blood flow restriction due to the forearm brace.

- As the cause of the rapid onset of forearm discomfort is as of yet unknown, more research is necessary to identify it. If it is known what exactly causes the discomfort, solutions that explicitly target those causes can be developed.
- Future research should particularly look into the role of the FDP muscle, the muscle that flexes the distal phalanges.

References


Appendix A  Overview of handhold and actuator attachments

A new handhold and several other components were designed and built for the muscle activation experiment and were attached to the hydraulic actuator. The handhold itself (Fig. 11, item 1) was attached to a crossbar (Fig. 11, item 4) with a 1.5 m long cable (Fig. 11 & 13). The cable ensured subjects were at a safe distance from the actuator and outside of its range of motion. The non-metal cable also ensured electrical insulation of the subject from the actuator setup. For additional protection of the subjects against excessive tensile forces, a magnetic coupling (Fig. 11 & 12, item 2), ensured the actuator would never exert a force of more than 370 N on the subject. The crossbar was attached to the actuator’s piston via a breaking rod (Fig. 11 & 13, item 5), designed to break in case of excessive bending moment. This is necessary to protect the force sensor.

Figure 11: Overview of the main components between actuator and subject. Starting from the right, the handhold assembly is shown (1), which is connected to the crossbar (4) via the magnetic coupling (2) and a cable (3). The crossbar is attached to the actuator (not shown) via the safety breaking rod (5)

A.1 Handhold

For a representative grip on the boom it was required that no parts of the handhold were forcing the fingers apart, as that could affect the grip[20]. The component that subjects actually held on to, part of a genuine boom, was a piece of 30 mm diameter, 200 mm long aluminium tube lined with EVA-foam grip material (Fig. 12, item 1). The handhold was secured by two threaded M5 steel rods (Fig. 12, item 4) and nuts, while 120 mm long aluminium tubes were used as spacers.
(Fig. 12, item 3). The aluminium U-beam is a 25x25x2 mm, 200 mm long component (Fig. 12, item 5). Detailed dimensions of the handhold can be found in App. M.

### A.2 Crossbar

To protect the actuator’s force sensor, the crossbar was attached to the actuator’s piston via a breaking rod (Fig. 11 & 13, item 5), which was designed to break in case of excessive bending moment. The crossbar contained two rollers (Fig. 13, item 1). These rollers allowed another cable (Fig. 13, item 4) to run through the crossbar. Two springs were attached to the ends of this cable. By having the subjects pre-tension these springs, the maximum force that the set-up could achieve was increased. The two ends of the cable run parallel to each other at a heart-to-heart distance of 90 mm. Two rollers, able to rotate within the crossbar’s U-beam, were used to guide the spring cable and to equalize cable tension on both sides and to avoid fiddly cable length adjustments. This design choice also prevents problems in symmetry from arising due to differences in spring stiffness, as the rollers ensure that the force in the cable is equalized on both sides. The rollers were held in place with a simple retaining clip. Stabilizers (Fig. 13, item 6) were installed prevent breaking of the breaking rod under compression, which was needed for calibration of the target position. A thought experiment with the breaking rod’s weak point acting as a hinge and being unable to transfer any bending moment at all, it is easy to see that the rod will collapse, when the spring cable is pulled and the end of the breaking rod is pushed, without stabilizers installed. This is because the arm of force in the cable becomes larger with a small deformation of the breaking rod. However, with the stabilizers in place, the arm of the cable force corrects small deformations, stabilizing the system. This allowed the actuator to push the crossbar out during calibration of the target position at 125 N spring force.

![Figure 13: Render of crossbar](image)

### A.3 Magnetic coupling

Even though the controller software limited the maximum actuator force at 180 N, there were concerns that in case of system failure an unexpected control input could cause a sudden high force could be exerted on the subject, potentially causing injury. To physically prevent the possibility
exerting excessive force on the subject a magnetic safety coupling was designed, built and incorporated within the cable between crossbar and handhold (Fig 11 & 12, item 2). It was calibrated to decouple at a tensile load of 370 N. More information on this coupling can be found in App. B and its dimensions can be found in App. N.

A.4 Springs

As at least 270 N was required for the experiment, but the actuator’s softeware was limited at 180 N, two springs were symmetrically installed between the cable ends and the table, parallel to the actuator. The spring constants were measured to be 445 and 475 N/m. The formula for calculating combined spring constant of two parallel (Hookean) springs of with spring constants $k_1$ & $k_2$ is

$$k_s = k_1[N/m] + k_2[N/m] = 445 + 475 = 920[N/m]$$
So the combined spring constant $k_s$ is 920 N/m. The maximum allowable load of an individual spring was 127 N according to factory specification (Roveron, Rotterdam, The Netherlands).
Appendix B  Magnetic safety coupling

In the unlikely case that the controller software that limits the pulling force at 200 N would fail, a much larger tensile force could potentially be exerted on the subject, which could result in injury to the subject. The hydraulic actuator’s piston used in the experiment has a surface area of $A_{piston} = 2.5cm^2(2.5 * 10^{-4}m^2)$. The actuator’s pump can deliver a maximum pressure of $P_{max} = 120bar(12 * 10^6Pa)$. In a worst case scenario, the maximum pressure acts on the piston resulting in the following maximum force:

$$F_{max} = A_{piston}[m^2] * P_{max}[Pa] = 3000[N]$$

To ensure the subject will not experience excessive tensile force, a magnetic coupling was designed, built and installed between handhold and hydraulic actuator.

B.1  Description

![Figure 15: A disassembled view (L) and an assembled view (R) of the magnetic coupling. The assembled view shows how the screws can be used to set an offset between magnet and steel plate.](image)

The coupling consisted of two steel plates, 10 mm thick, between which a 13 x 25 x 25 mm neodymium magnet is placed. Both plates contained a 5mm hole in the middle through which it connects to the handhold and the hydraulic cylinder. A slot on one steel plate ensured the magnet is placed in the center of the holes. The magnetic force, and thus maximum transferable force, depends strongly on the distance between the magnet and the steel plate. Three M6 screws with a 1.00 mm pitch could be used to create an offset between magnet and one steel plate. By increasing the offset, the maximum force the coupling could transfer reduced, allowing calibration to ensure decoupling at the desired force. The metal plates had conical holes the screws could sink into. This ensured alignment of the central holes in the metal plates, and thus alignment of the cables, which were attached in line with those holes. The M6 screws also provided protection of the magnet; they prevented the unconnected metal plate from slamming into the brittle magnet when coupling. The two steel plates and magnet weighed 340 gr. Detailed dimensions of the magnetic coupling can be found in Appendix N.
B.2 Testing

Tests with various offsets were conducted, to determine the maximum tensile force the coupling could transfer with each offset. The same screws and nuts were used during the muscle activation experiment, as the presence of ferromagnetic metal could affect the maximum force the coupling could transfer. The maximum force corresponding to a certain offset was measured using the following procedure:

- Couple the steel plates and magnet.
- Adjust screws so that they contact the other steel plate, but do not create an offset between magnet and steel plate yet.
- Turn each screw the appropriate number of degrees to achieve the desired offset. Example: to create a 1 mm offset, the M6 screws (pitch = 1 mm) each have to be rotated 360°.
- Use the nuts on the screws to fix the screws in this position, to prevent accidental adjustment.
- Increase tensile force until magnetic coupling released.

Each offset was tested three times. Between repetitions with the same offset, the screw setting was not changed.
B.3 Test results

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Table 2: Maximum forces measured during for each repetition, and their average values

During the the experiment, the magnetic coupling was used with an offset of 0 mm. This corresponds to a force transfer capability of 370 N. With a maximum force that should be experienced by a subject at 270 N (Based on an 80 kg subject), the magnetic coupling should never decouple, unless the control software stopped functioning and a sudden, high force was exerted. No situations occurred where the coupling decoupled during the muscle activation experiment.

Figure 17: Graph with the results of magnetic coupling maximum force transfer as a function of the offset between magnet and steel plate
Appendix C  Prototype

C.1  Design

A test prototype was custom made for the muscle activation experiment, instead of modifying an existing wrist brace. Because wrist mobility was thought to be important for windsurfing, one of the goals was to test a brace that only attached to the lower arm did not restrict wrist movements. The prototype is fabricated mainly by 1 mm thick woven nylon straps of various widths, which are stitched together with high strength thread. The brace is tightened to the forearm using 3 nylon and Velcro tightening straps, which loop around the arm and through steel loops and are tightened using the Velcro (Fig. 18). By using three separate tightening straps, the prototype can be adjusted to the lower arms local circumference at the locations of the straps, to help distribute the forces on the forearm.

Figure 18: A render of the prototype’s main body. Blue material is hook-type Velcro \((\text{1})\), the red material is loop-type Velcro \((\text{2})\). Stitching locations are shown in white \((\text{3})\).

Figure 19: A render of both the prototype’s supports. The red material is loop-type Velcro \((\text{1})\). Stitching locations are shown in white \((\text{2})\).

Perpendicular to the straps around the arm there was a nylon strap which could partly transfer pulling force from the boom to the arm (Fig. 18, item 4). The prototype should be placed on the forearm such that that strap runs parallel to the handpalm. A buckle was used to adjust the length of the nylon strap such that the hand was in a comfortable position on the boom when the strap was taut (Fig. 18, item 5). Between the boney sides of the arm and the nylon straps there was
extra padding in the form of 5 mm thick neoprene (Fig. 19). Loops were stitched on the neoprene to guide the three tightening straps and keep the supports in place. The padding reduces possible pressure points, and was also meant to reduce pressure on the wrist’s carpal tunnel. A reduced pressure at the carpal tunnel allows blood to flow to the hands more easily, keeping them warmer. More detailed dimensions of the prototype can be found in Appendix O - S.

C.2 Donning the prototype

To simulate that the brace would be worn in combination with a wetsuit, a neoprene sleeve from a wetsuit was worn under the prototype. Then, the regular neoprene glove was put on (Fig. 20). After that the prototype was put on, ensuring the aluminium buckle was parallel to the handpalm with the fingers stretched out (Fig. 21). Care was taken that the tightening straps were not too tight for the subject’s comfort by repeatedly verbally reminding the subject it shouldn’t feel uncomfortably tight. Care was taken that the EMG electrodes (not shown) were not disturbed by the sleeve or prototype, as that could affect the measurements. Finally the boom strap was looped around the boom and back through the aluminium buckle (Fig. 21). The buckle was used to adjust the length of the strap such that the fingers could hold the boom in a normal boom-holding posture, when the strap was taut.
Figure 22: Looping the boom strap around the boom and back through the buckle
Appendix D  Handhold force

The average harness line force has been measured by Walls and Gale (2001)[19] to be half the bodyweight. Had the harness not been used, and the sailor had been in the exact same position, all force from the sail would be transferred through the arms. Assuming equal distribution of this force between both arms, the average force each subject should experience during the experiment, should then be a quarter of his bodyweight, as only one arm is used in the force transfer. The effects of two disturbances on the average pulling force are modeled, the assumptions and reasoning for estimating their magnitudes and frequencies are explained in Section D.1 & D.2.

D.1 Wave disturbance

When windsurfers ride across waves, they experience vertical accelerations $a_{vert}(t)$. Assuming the sailor’s body position remains the same, the horizontal force $F_{pull}$ they need to transfer through their arms fluctuates, as the sum of moments (about the feet) needs to remain zero to maintain equilibrium. As the vertical acceleration is the second derivative of position, an estimate for the windsurfer’s vertical position in time $p_{vert}(t)$ is needed. It was assumed that the windsurfer moves across a sinusoidal surface, which represents the water surface with waves, which itself moves in the opposite direction as the windsurfer. The windsurfer’s velocity $v_{windsurfer}$ was estimated and assumed to be a constant 9 m/s. Wave speed (or phase velocity) $v_{wave}$ and wave length $L_{wave}$ are functions of the water depth and wave period[17].

Assuming a top-to-bottom wave height $2 \times A_{wave}$ of 2 m, a wave period $T_{wave}$ of 8 seconds and a water depth of 5 m, a wave speed and wave length estimation was obtained; respectively 7 m/s and 60 m (Fig. 24). The same figure shows that with a water depth of 5 m, waves with a 8 s period would have a wave length $L_{wave}$ of about 60 m.

A combined windsurfer speed and wave speed of $v_{windsurfer} + v_{wave} = 7 + 9 = 16$ m/s, means the windsurfer reaches a wave peak every 3.75 seconds.

$$\frac{L_{wave}}{v_{windsurfer} + v_{wave}} = \frac{60}{16} = 3.75s$$
Figure 24: Two graphs showing the relation between wave length, phase velocity and wave period for several waterdepths. Figure courtesy of http://www.seafriends.org.nz/oceano/waves.htm[1], where it was adopted from van Dorn (1974)[17]

So the windsurfer essentially travels across a sinusoidal surface with a frequency of $1 / 3.75 \text{s} = 0.2667 \text{Hz} (1.67 \text{rad/s})$ and an amplitude of $A_\text{wave} = 1 \text{m}$.

The following equations for the windsurfer’s vertical position $p_\text{vert}(t)$, velocity $v_\text{vert}(t)$ and acceleration $a_\text{vert}(t)$ in time, were obtained with $A_\text{wave} = 1 \text{m}$ and $f = 1.67 \text{rad/s}$.

$$p_\text{vert}(t) = A_\text{wave} * -\sin(f * t)$$

$$\dot{p}_\text{vert}(t) = v_\text{vert}(t) = A_\text{wave} * f * -\cos(f * t)$$

$$\ddot{p}_\text{vert}(t) = a_\text{vert}(t) = A_\text{wave} * f^2 * \sin(f * t)$$

By using a simplified model of a windsurfer, which assumes the sailor’s body remains rigid, and hanging at a set angle, the effect of vertical accelerations on the pulling force can be calculated (Fig. 23). Working with the assumption that the pulling force transferred by the arms is half the sailor’s body weight ($F_\text{pull} = 0.5 * m g$) when no disturbances are present ($a_\text{vert}(t) = 0$), and that no moments are transferred through the sailor’s hands or feet ($M_\text{feet} = M_\text{hands} = 0$), the relation between $b$ and $c$ can be obtained, for this particular sailor position. Additionally, the assumption is made that the $F_\text{pull}$ is purely horizontal such that $F_\text{y hands} = 0 \text{N}$.

$$\sum M_\text{feet} = M_\text{hands} + M_\text{feet} + m * (g + a_\text{vert}(t)) * c - F_\text{pull} * b = 0$$

$$m * (g) * c = 0.5 * m * g * b$$

This reduces to

$$\frac{c}{b} = 0.5$$

Now that the relation between $b$ and $c$ is known, the effect of $a_\text{vert}(t)$ on can be computed for this sailor position.

$$F_\text{pull}(t) = \frac{c}{b} * m * (g + a_\text{vert}(t)) = 0.5 * m * (g + a_\text{vert}(t))$$
Substituting $a_{vert}(t)$ into the equation

$$F_{pull}(t) = 0.5 m \cdot (g + (A_{wave} \cdot f^2 \cdot \sin(f \cdot t)))$$

Note that this equation for $F_{pull}$ does not yet include the effects of wind speed fluctuations described in Section D.2

**D.2 Wind disturbance**

In real life, windsurfers generally go faster with higher wind speeds. Velocity changes affect both the apparent wind speed and angle, and sailors need to adjust body position and sail angle to the new situation. Aerodynamic factors like the sails lift/drag coefficients, but also hydrodynamic factors like board and fin drag each influence on the new speed. Also, sailor skill needs to be considered; a skilled sailor will be able to go faster than a sailor with a lower skill-level, with all other variables being equal.

To simplify the effects of wind velocity fluctuations (gusts and lulls) on the sail force, a 10% increase from the mean velocity was assumed to result in a 10% increase in sail force. Obviously this is a gross simplification of reality, but time did not allow for an extensive analysis of this effect, and also was not the goal of the research.

A graph of windspeed data was obtained from Wu et al. (2012)[21]. 40 seconds of this 1000 second signal were chosen to be used in the experiment (Fig. 25).

![Wind Speed Data](image)

**Figure 25:** The selected 40 seconds of wind speed data is shown between the red lines. Image modified from Wu et al.[21]

The 40 second signal was scaled with a factor of 1.1625 in order to make the average wind velocity 11 m/s (6 Bft)(Fig. 26), a common wind velocity for ocean sailing. Still working with the average pulling force of half the body weight, a disturbance signal was created for an 80kg subject, which was divided by two, for the pulling force on one hand. This results in the disturbance force signal in Fig. 27.
**Figure 26:** The raw and scaled wind speeds

**Figure 27:** Wind disturbance force for an 80kg subject
D.3 Force signal in experiment

![Force signal graph](image)

Figure 28: Force resisted by a subject with a body weight of 80 kg

The force signal used in the experiment is composed of the bias of half the subject’s body weight, the force disturbances from wind velocity fluctuations and vertical accelerations as a result of waves. One signal was first made for a 80 kg subject (Fig. 28), and because all both the wind and wave disturbances and the bias force were linearly dependent on the subjects body weight, that signal could be, and was, scaled to each individual subject.

Before the actual force signal started, the subject pre-tensioned the springs at 125 N, by pulling the handhold to the target position. The actuator software then took 5 seconds to raise the pulling force to the appropriate bias force for each particular subject. At $t = 5$ s, the disturbances were activated. After the wind disturbance signal ended at $t = 45$ s, one more second was added to reduce prevent the subjects feeling a shock when the actuator disturbances were disabled. The result is shown in Fig. 28 for an 80 kg subject.

D.4 Force transfer to handhold

![Force transfer diagram](image)

Figure 29: Forces acting on crossbar

For the experiment design, it was important that subjects experienced the same force signal $F_{pull}(t)$ during each trial. The target position $P_{target}$ of the handhold, which was defined as the
handhold position where the springs had a combined pulling force of 125 N (Fig. 29) the actuator software was able to track a reference force signal \( F_{ref}(t) \), however this force signal needed to compensate in real time for position deviations \( p_e(t) \) from the target position. The combined spring stiffness \( k_{spring} \) of the springs was measured to be 920 N/m, so the controller software could use that value combined with the readings from the actuator’s position sensor to calculate the current spring force. The force on the handhold \( F_{handhold}(t) \) needed to be equal to \( F_{pull}(t) \), which was known in advance; see section D.3. \( F_{handhold}(t) \) however, was given by the following formula:

\[
F_{handhold}(t) = 125 - p_e(t) \cdot k_{spring} + F_{ref}(t) = F_{pull}(t)
\]

In order to make handhold force \( F_{handhold}(t) \) equal to the desired pre-determined pulling force \( F_{pull}(t) \), the controller used several inputs, variables and constants to calculate what \( F_{ref} \) should be as in Figure 30. Here, the bodyweight is whatever weight was entered for a particular subject, which is used determine the bias force and to scale the disturbance forces. The disturbance forces are stored as the forces an 80 kg subject should feel in look-up tables that give their outputs depending on the time, given by the clock, which starts at \( t = 0 \) s. The summation of both look-up tables is divided by 80, to get a normalized disturbance force, after which it is multiplied by the variable Bodyweight to produce scaled disturbance signal for each particular subject. As the spring force has not yet been accounted for in sum of the bias and disturbance forces, it needs to be subtracted from the signal sent to the actuator’s controller. The force in the springs was fully determined as the actuator’s position was measured and processed in real-time. The position error \( p_e(t) \) (defined as the distance from the target position) was multiplied by the spring stiffness \( k_{spring} \). The result was subtracted from the spring force at the target position (125 N), to obtain the force in the springs in real time \( F_{spring}(t) \). This force was subtracted from the bias and disturbance forces, to produce \( F_{ref}(t) \). This controller setup ensured each subject experienced the same force signal, scaled to his particular Bodyweight, during each trial, independent of any position errors.

Figure 30: Block diagram showing how the controller used several inputs, constants and variables to calculate the force \( F_{ref} \) the actuator should apply
Appendix E  Protocol

E.1  Hardware inspection

Ensure the springs are unattached to the handhold, to protect the setup in case the cylinder moves to its maximum stroke position.
Check the safety breaking rod condition and replace if damaged.
Check the condition of cables for wear or other damage and replace if necessary.
Check that the magnetic safety coupling (App. B) is aligned correctly, and its spacing screws are centered in their respective holes.
Turn the knob on the analog computer to the correct position, so that it works with a 200N maximum.

Figure 31: Several required small items: Sandpaper, rubbing alcohol and clean pad, tape measure, pen, and new razor blade

Figure 32: Top: Delsys Dermatrode reference electrode and bottom: EMG electrodes and stickers. Images modified from and used with permission of Delsys
Make sure all materials are readily available before the subject arrives:

- 4 Delsys 2.1 EMG-electrodes (Fig. 32), labeled FDS, ED, ECR and FCR on both sides of the wire (Fig. 35), prepared with new electrode stickers (Delsys Adhesive Sensor Interface)
- Reference electrode (Delsys Dermatrode Reference Electrode)(Fig. 32)
- New razor blade (Fig. 31)
- Sandpaper (Fig. 31)
- Rubbing alcohol (Fig. 31)
- Gloves, low stiffness gloves, prototype (Fig. 33)
- Piece of wetsuit sleeve (Fig. 33)
- Pen (Fig. 31)
- Fatigue evaluation forms (App. K)
- A little seawater in a bowl
- Sponge
- Scale
- Tape measure (Fig. 31)

Figure 33: The items needed for the various experiment conditions

E.2 System start up

Turn on the main computer and PC.
Turn on 19th rack for the analog side of the controller.
Open the main hydraulic valve.
Enable the controller of the hydraulic cylinder by turning the switch from 0 to 1, and press the green button.
If necessary, reset the safety switch. The controller now controls the hydraulic cylinder.
Set the analog side to $m = 1.5\text{kg}$, 0 stiffness and 0 damping.
Adjust the fine adjustment for the force sensor gain so that the actuator remains still.

E.3 Subject preparation

Have the subject read and fill out the consent form (App. J).
Weigh subject using the scale and record on consent form.
Measure subject palm and middle finger length using the tape measure and record on consent form. Give subject an anonymized code: Subject number + Initials. (For example: The fifth subject John Doe would be 05JD).

Start up the experiment protocol on the PC and follow the instructions on screen. Let the subject train with each condition to familiarize him with the conditions and the set-up. Ensure the subject understands that the experiment goal is to remain as relaxed as possible, and not that he remains at the target position as good as possible. Circle the spots on the subject’s arm where you can feel the muscle harden the most when the subject activates this muscle (Fig. 34).

![Figure 34: Indication of the where the ED and the ECR electrode should be placed, before shaving the subject.](image)

Ensure the subject’s arm is in an outstretched, forward position with the palm down. Label each spot with the corresponding muscle abbreviation (FDS, ED, ECR, FCR) to avoid confusion. Use a new razor blade to remove any hair around the circled spots. Use the sandpaper to clear the dead skin cells from the circled spots. Use rubbing alcohol to remove oil or grease from the circled spots. Remove the protective film from the EMG-electrodes, and place the now adhesive electrode on the circled spots. Ensure that the electrode is placed in the muscles’ longitudinal direction, with the wire running in the direction of the elbow. Ensure the labels on the electrodes match the markings on the skin. Have the subject stretch his arm forward with the palm down, and stick the earth electrode on the bony part of the elbow. Connect the all electrodes to the marked sockets on the Delsys Input Module.

(FDS: channel 5, ED: channel 6, ECR: channel 7, FCR: channel 8) (Fig. 35).

Ensure the cable from the Input Module is connected properly to the Delsys Bagnoli-16 EMG System main amplifier (Fig. 36). Ensure the main amplifier has power and is turned on. Check that cables from main amplifier to A/D converter are properly connected and in the right connections (channel 5: 25, channel 6: 26, channel 7: 27, channel 8: 28). Turn the amplification to 10k on each channel. Ask subject to activate the muscles and check that the corresponding light blinks. If the subject saturates a channel, turn the amplification level down to 1k. If subject can still saturate that channel, turn the amplification level down to 100. Repeat for all channels/muscles, and turn off the beeping function for saturation. On the PC, run the next part of the protocol, which takes a baseline EMG reading from each muscle for 30 seconds.
Glove effects on forearm muscle activity in a windsurfing-like task

Figure 35: Delsys 1-8 Input Module, showing the EMG electrode cables with their labels on the right, earth electrode cable on top, and data cable to the main collection box on the bottom

Figure 36: Delsys Bagnoli-16 EMG System or main amplifier, showing the label indicating each muscle to the corresponding EMG-channel (top) and A/D converter channel (middle)

During this time, ask subject to squeeze his fingers (FDS), then stretch his fingers (ED), then lift his hand up while relaxing his fingers (ECR) and tilt his hand down while relaxing his fingers (FCR).

The remainder of the time the subject should put his arm on the table, outstretched and relaxed. Ensure that the EMG electrodes do not get trapped between arm and table.

Inspect the results which automatically pop-up to see whether the electrodes pick up the correct muscle activity and its also decoupled sufficiently from the other muscles.

If this is the case, continue with the experiment.

If this is not the case, reposition the electrode and repeat.

E.4 Experiment

If there is enough light coming in from outside, turn off the TL-lights to reduce interference with the EMG equipment.

Continue with the protocol on the PC. This automatically randomizes conditions and tells you the
order of the conditions for testing.

Before each trial:

- Have subject put on glove, low stiffness glove, prototype or remain bare-handed, depending on condition order
- Ensure the subject receives a few minutes of rest between trials, so that the arm is not fatigued when the trial starts.
- Dab the wet sponge on the handhold surface and hand palm.
- Visually check that the subject’s position is correct.
- Ask subject to pre-tension the springs when he is ready.

Start trial when the subject holds the handhold at the target position.

After the last repetition of each condition, ask the subject to fill out a fatigue evaluation form (Appendix K) of the corresponding condition. Ensure he cannot see any fatigue forms he has filled out earlier.
Appendix F  Experiment logbook

A logbook was kept during the experiments. If nothing out of the ordinary happened during the experiments, nothing was logged. Initially, the goal was to perform the experiments with the TL-lights off, as they can increase electrical interference to the EMG electrodes. As the first subjects were done in December, it was quite dark outside and not a lot of light came in. Upon inspection of the results, the electrical interference did not seem to affect the measurements too much, as the frequency content did not seem show excessive spikes around the 50, 100 or 150 Hz frequencies. After that it was decided to do all experiments with the lights on, possibly accepting a little more interference, but keeping the conditions the same between subjects.

12-dec-13

Subject 01:
Dr.ir. W. Mugge was present with the first subject to assist and prevent possible mistakes. The subject was fairly muscular and identifying the muscle locations and applying the EMG-electrodes did not pose any difficulties. All EMG pre-amplifications were set at 1k.

17-dec-13

Subject 02:
After the EMG-electrodes were placed and the measurements were about to start, the building’s fire alarm went off and the building had to be evacuated. The subject was never in danger as it turned out to be a false alarm. The subject returned the day after to retry doing the experiment.

18-dec-13

Subject 03:
The subject was fairly muscular and toned, so identifying the muscle locations and applying the EMG-electrodes did not pose any difficulties. All EMG pre-amplifications were set at 1k. During the tenth trial (glove, repetition 3), the subject reported his foot started to cramp. The trial was finished and the subject rested until he verbally communicated he was ready to continue.

Subject 02:
This was the subject who the day before had to leave due to the fire alarm. For this subject, properly placing the EMG-electrode on the FDS muscle was for some reason problematic. It took three attempts before its placement was acceptable. The other EMG electrodes did not pose difficulties. All EMG pre-amplifications were set at 1k.

Subject 04:
Electrode placement on the FDS again proved difficult, requiring re-placing the electrode 4 times. Once placed correctly it was noticed that the subject could saturate the channel on the main amplifier (at the time pre-amplified at 10k), by flexing the pinky, but not by flexing any of his other fingers separately. For the experiment all EMG pre-amplifications were set at 1k. During the experiments, it was noticed after the second repetition that the reference electrode on the elbow was half loose. It was stuck back to the skin and did not come loose during the third trial. Upon inspection after the last trial, nothing out of the ordinary was seen in the EMG data during the first 2 repetitions. After the 10th trial (glove, repetition 3), subject let go of the handhold a split-second too soon, and the actuator fully retreated it’s cylinder, which sent its software into a fault condition. Fortunately this happened after the experiment’s data was saved, and the experiments could be continued as normal.
**Glove effects on forearm muscle activity in a windsurfing-like task**

April 28, 2014

**Subject 05:**
Electrode placement did not pose any difficulties and all pre-amplifications were set at 1k. Just before commencing the third trial (prototype, repetition 1), the subject clumsily pulled on the handhold in the wrong direction, breaking the safety breaking rod that protects the force sensor. The safety breaking rod was replaced and the experiment continued. At about 10 s before the end of the 11th trial (glove, repetition 3), the handhold partially slipped from the grip causing quite a large position shift to recover. During the last trial (bare hand, repetition 3), subject verbally communicated that his arm was getting fatigued.

19-dec-13

Subject 06:
Subject had very little body fat and muscles were easy to find. EMG-electrode placement did not pose any difficulties and all pre-amplifications were set at 1k. Subject reports during fourth trial (glove, repetition 1) that his hand slipped on the inside of the glove a little bit.

15-jan-14

Subject 07:
For this subject, it was difficult to identify the ECR muscle, as it seemed to lay beneath the ED muscles. In the end, a location was found where there was some activity picked up from wrist extension, but not so much that it would saturate the channel at 10k pre-amplification, so that pre-amplification was kept. The electrodes for the other muscles were pre-amplified at 1k. During the 5th trial (bare hand, repetition 2), subject came forward too far and to correct that suddenly exerted too much force on the handhold, causing the actuator to go into safety mode, and the trial finished. To compensate, another measurement was done with the bare hand under another name. When continuing with the original program, it wanted to do the same trial again (which I didn’t expect), as the measurement. I should have, at that point, taken the subject’s place in that trial, and manually replaced the data properly, however I let the subject do the trial again, so he did 4 bare hand trials, and 13 in total.

16-jan-14

Subject 08:
Electrode placement did not pose any difficulties and all pre-amplifications were set at 1k. After the 5th trial (glove, repetition 2), the subject reported his knees were starting to hurt a little bit. After that, longer breaks were taken between trials to ensure the subject was comfortable. During the 10th trial (prototype, repetition 3), the subject did the same thing as subject 07, causing the actuator to go into safety mode. I had by then learned more about how the program dealt with that situation, so I could stop the measurement on the PC, which caused the program to redo the last condition and no other programs had to be started.

Subject 09:
Electrode placement did not pose any difficulties and all pre-amplifications were set at 1k. Nothing out of the ordinary happened.

Subject 10:
Electrode placement did not pose any difficulties and all pre-amplifications were set at 1k. Nothing out of the ordinary happened.
Appendix G  Subject summary

G.1  Subject summary

Table 3: Summary of subject information

<table>
<thead>
<tr>
<th>Subject number</th>
<th>Start Time</th>
<th>Date</th>
<th>Glove size</th>
<th>Palm Length [cm]</th>
<th>Middle finger length [cm]</th>
<th>Body weight [kg]</th>
<th>Height [m]</th>
<th>Age [Years]</th>
<th>BMI</th>
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<td>12-dec-13</td>
<td>L</td>
<td>18.3</td>
<td>8.3</td>
<td>75.5</td>
<td>1.74</td>
<td>27.9</td>
<td>24.9</td>
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<td>18-dec-13</td>
<td>L</td>
<td>19.5</td>
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<td>81.4</td>
<td>1.80</td>
<td>22.2</td>
<td>25.1</td>
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<tr>
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<td>1.83</td>
<td>31.2</td>
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<td>L</td>
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<td>8.7</td>
<td>82.9</td>
<td>1.96</td>
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<td>1.84</td>
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<td>L</td>
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<tr>
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<td></td>
<td>18.9</td>
<td>8.3</td>
<td>76.5</td>
<td>1.82</td>
<td>26.9</td>
<td>23.1</td>
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<tr>
<td>Standard deviation</td>
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<td></td>
<td></td>
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<td>0.4</td>
<td>6.3</td>
<td>0.07</td>
<td>2.70</td>
<td>1.5</td>
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</table>

G.2  EMG pre-amplifications per subject

Table 4: Pre-amplification settings per subject as used in the experiment

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<tr>
<th>Subject code</th>
<th>FDS amplification [-]</th>
<th>ED amplification [-]</th>
<th>ECR amplification [-]</th>
<th>FCR amplification [-]</th>
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<td>10</td>
<td>1k</td>
<td>1k</td>
<td>1k</td>
<td>1k</td>
</tr>
</tbody>
</table>

Note that only one pre-amplification was not 1k; the pre-amplification for subject 7’s ECR electrode. This was done because during electrode placement, the subject was not able to saturate the corresponding channel by activating his ECR by extending his wrist. Using a higher pre-amplification in such a case makes the measurement more sensitive.
G.3 Trial order per subject

Table 5 shows the trial order of the experiments, for all subjects. The trial order was randomly determined by the computer, at the start of the experiment with a particular subject. Note that the order, even though pre-determined was not yet visible to the researcher or the subject. When a trial finished, the condition for only the next trial was shown.

Table 5: Condition order per subject. 1 - Bare hand, 2 - Glove, 3 - Low stiffness glove, 4 - Prototype

<table>
<thead>
<tr>
<th>Subject</th>
<th>Repetition 1</th>
<th>Repetition 2</th>
<th>Repetition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>1 - 2 - 4 - 3</td>
<td>3 - 1 - 4 - 2</td>
<td>4 - 1 - 2 - 3</td>
</tr>
<tr>
<td>02</td>
<td>2 - 4 - 3 - 1</td>
<td>1 - 2 - 4 - 3</td>
<td>3 - 2 - 4 - 1</td>
</tr>
<tr>
<td>03</td>
<td>4 - 1 - 2 - 3</td>
<td>3 - 1 - 4 - 2</td>
<td>1 - 2 - 3 - 4</td>
</tr>
<tr>
<td>04</td>
<td>4 - 1 - 3 - 2</td>
<td>2 - 3 - 4 - 1</td>
<td>4 - 2 - 1 - 3</td>
</tr>
<tr>
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<td>06</td>
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<td>1 - 2 - 4 - 3</td>
<td>1 - 4 - 3 - 2</td>
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<tr>
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<td>1 - 3 - 4 - 2</td>
<td>2 - 4 - 3 - 1</td>
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<td>2 - 1 - 4 - 3</td>
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<td>4 - 2 - 1 - 3</td>
<td>4 - 1 - 2 - 3</td>
<td>3 - 2 - 4 - 1</td>
</tr>
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</table>
Appendix H  EMG filtering

This appendix describes the filtering process of one EMG signal. To be able to better show the process, only 2.2 seconds of the full 46 second signal is shown. A full length example is shown in Fig 42, at the end of this appendix. All EMG data in this appendix are from the Flexor Digitorum Superficialis muscle, from the first repetition of the bare hand condition of subject 1.

Figure 37: Raw EMG data

![Raw EMG data](image)

Figure 38: Electrical interference from the building’s electrical mains removed. In this case there was not a big difference, as can be seen from the fact that the red signal almost completely overlaps the blue signal.

In Fig. 38, the same unfiltered signal is shown in blue as in Fig. 37, together with the signal in red that had the 50, 100 and 150 Hz frequency components removed using a discrete Fourier transform. Those frequencies were removed to eliminate possible interference from the building’s 50 Hz electrical mains.
Fig. 39 shows the result after taking the signal with possible interference removed through a second-order non-causal high-pass Butterworth filter with a cut-off frequency of 20 Hz. This filter is used to remove any possible strange attenuation phenomena associated with the lower cut-off frequency of the Bagnoli desktop amplifier’s 20 - 450 Hz bandpass filter.

The high pass signal is subsequently rectified in Fig. 40, which means all values are taken as absolute values. The result is that the signal no longer contains negative values.
Finally a low pass filter is applied to the rectified signal, to create Fig. 41. The low pass filter was a second-order non-causal low-pass Butterworth filter with a cut-off frequency of 3 Hz [14].

The same signal as in Fig. 41 is shown in Fig. 42, but over the full time span of the experiment. Note that the first 5 seconds of the filtered signal have been removed, as the force disturbance was not applied during this time. The average value of the filtered signal from $t = 5$ to $t = 46$ is taken process. For this particular signal, the average value was 0.0597 V.
Appendix I  EMG measurement summary

This section contains tables with the mean EMG measurement values, divided per muscle. There are two tables for each muscle, the first containing the means of all repetitions, the second contains the mean value of all three repetitions, which is used in the statistical tests.

I.1 Flexor Digitorum Superficialis (FDS), finger flexor

<table>
<thead>
<tr>
<th>Replication</th>
<th>Bare hand</th>
<th>Glove</th>
<th>LSGlove</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 rep 1</td>
<td>0.0597</td>
<td>0.0706</td>
<td>0.0460</td>
<td>0.0221</td>
</tr>
<tr>
<td></td>
<td>0.0427</td>
<td>0.0577</td>
<td>0.0463</td>
<td>0.0296</td>
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<tr>
<td></td>
<td>0.0396</td>
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<td>0.0269</td>
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Figure 43: Average EMG measurement values [V] of the Flexor Digitorum Superficialis muscle
I.2 Extensor Digitorum (ED), finger extensor

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Figure 44: Average EMG measurement values [V] of the Extensor Digitorum muscle
### I.3 Extensor Carpi Radialis (ECR), wrist extensor

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|    | 02 mean  | 0.0030 | 0.0042 | 0.0035 | 0.0022 |
|    | 03 mean  | 0.0190 | 0.0383 | 0.0321 | 0.0030 |
|    | 04 mean  | 0.0246 | 0.0251 | 0.0290 | 0.0032 |
|    | 05 mean  | 0.0281 | 0.0265 | 0.0283 | 0.0048 |
|    | 06 mean  | 0.0104 | 0.0196 | 0.0073 | 0.0023 |
|    | 07 mean  | 0.0120 | 0.0076 | 0.0117 | 0.0045 |
|    | 08 mean  | 0.0120 | 0.0141 | 0.0158 | 0.0058 |
|    | 09 mean  | 0.0030 | 0.0040 | 0.0034 | 0.0023 |
|    | 10 mean  | 0.0046 | 0.0044 | 0.0044 | 0.0022 |

Figure 45: Average EMG measurement values [V] of the Extensor Carpi Radialis muscle. Note that bold printed values have been corrected for different pre-amplification settings.
### I.4 Flexor Carpi Radialis (FCR), wrist flexor

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<td>0.0875</td>
<td>0.0978</td>
<td>0.0483</td>
</tr>
</tbody>
</table>

Figure 46: Average EMG measurement values [V] of the Flexor Carpi Radialis muscle
Instruction and consent form - Muscle activation experiment

Name: 
Address: 
Telephone number: 
Sex: M/F 
Date of birth: / /19 
Height: cm 

Your personal information will never be published or sold and is only stored for administrative purposes. You are free to access your information or experiment data if you wish. 

By signing this form you declare to 

- Be in good health and that you do not have any injuries or conditions that negatively affect the use of your upper limbs. 
- Give the researcher permission to store your personal information for up to six months after signing. 
- Have read and understood this entire form. 

Time: Date: Signature: 

Below here to be filled in by researcher. 

Subject IDcode: Subject number (two digits) + Initials (Piet Jansen as subject number 3: 03PJ) 
Glove size: (M/L/XL) 
Body Weight: kg (measure) 
Palm length: cm (base of hand to middle finger tip, palm side) 
Middle finger length: cm (base to tip, palm side)
**Instructions**

The experiment you are about to do consists of twelve 45-second trials of you holding a handhold at a target position, visually shown to you on a computer monitor. The target position will pre-tension springs, requiring a pulling force of roughly 20 kg. The handhold is attached to a hydraulic actuator, which will apply deviations to the pulling force, which you will need to suppress to maintain your position. Prior to the actual experiment you will do a training trial, to get used to the experiment. In random order you will then perform this task bare handedly (3x), with gloves on (3x), with low stiffness gloves (3x), and with a test prototype (3x).

Your instructions are to sit down on the mattress on your knees, facing the monitor, and resist the pulling force with an outstretched arm.

You are to hold the handhold near the target position, using your shoulder muscles and body position, as energy-efficient as possible. That means you need to use your muscles in such a way that you feel you can perform the task for the longest amount of time.

Surface EMG-electrodes (ElectroMyoGraphy) will be placed on your arm, to record your muscle activation during the experiment. These electrodes only record; they do not actively put a voltage on you. Please be aware of the wires attached to the electrodes, so they do not get snagged on anything. Before the experiments, the EMG is calibrated. This is done by resting your arm on a table and relaxing your muscles in the same position as during the experiment.

As your safety is the #1 priority, both mechanical and programmed safety precautions should prevent excessive forces that could cause injury to ever occur. In case you feel that the exerted force is too large for your arm, you are of course allowed (and encouraged!) to let go. If you have any concerns or questions about safety, please ask!

**Remarks**

- If you feel tired and are in need of a break, please tell the researcher.
- If for any reason you do not wish to continue with the experiment, you are at any moment free to do so.
- If you have any questions or concerns, you can direct them to the researcher Nigel Mulders or his supervisor dr.ir. G. Tuijthof.

Thank you for participating!

Signature:     Date:
Fatigue estimation

Subject code:

On the line below, please put a vertical stripe on the horizontal line to mark the position you feel best represents how tiring you experienced the **bare hand** condition. On the line the left end represents “not tired at all”, and the right end represents “as tired as can be”

Fatigue estimation

Subject code:

On the line below, please put a vertical stripe on the horizontal line to mark the position you feel best represents how tiring you experienced the **glove** condition. On the line the left end represents “not tired at all”, and the right end represents “as tired as can be”

Fatigue estimation

Subject code:

On the line below, please put a vertical stripe on the horizontal line to mark the position you feel best represents how tiring you experienced the **low stiffness glove** condition. On the line the left end represents “not tired at all”, and the right end represents “as tired as can be”

Fatigue estimation

Subject code:

On the line below, please put a vertical stripe on the horizontal line to mark the position you feel best represents how tiring you experienced the **test prototype** condition. On the line the left end represents “not tired at all”, and the right end represents “as tired as can be”
Appendix L  Drawing Crossbar

Crossbar Assembly

TU Delft  Mechanical Engineering

name  Crossbar Assembly  units  mm
scale  1:2  date  27-4-2014  mass  gram
signed  N.M.Mulders  formaat  A4  drawing number  group
Appendix M  Drawing Handhold

Handhold Assembly

TU Delft
Mechanical Engineering

name
Handhold Assembly

scale 1:2
date 27-4-2014
mass
signed N.M.Mulders

TU Delft
Mechanical Engineering

format A4
drawing number

units mm

name
Handhold Assembly

scale 1:2
date 27-4-2014
mass
signed N.M.Mulders

TU Delft
Mechanical Engineering

format A4
drawing number

units mm
Appendix N  Drawing Magnetic Coupling

Magnetic coupling

TU Delft
Mechanical Engineering

scale 1:1  date 27-4-2014  mass
signed N.M.Mulders  gram

format A4  drawing number

name units mm

R1
20
25
60
13
20
20
R7
30
5

TU Delft

30
5
R1
20
25
20
10
10
20
13
10
10
16
16

Appendix P  Drawing Velcro Support Loops

Velcro loops support

TU Delft
Mechanical Engineering

name

units
mm

scale 1:1.5
date 7-3-2014
mass 70 gram

signed N.M.Mulders

format A4

drawing number

group

Loop-type Velcro
Appendix Q  Drawing Support Loops

Loop support

TU Delft
Mechanical Engineering

name
signee

units

mm

scale
date
mass

1:1.5
7-3-2014
82 gram

A4
drawing number

format

mm
Appendix S  Drawing Buckle

Mat.: Aluminium

Aluminium buckle

name: Aluminium buckle

TU Delft
Mechanical Engineering

scale: 2:1  date: 27-4-2014  mass: 5 gram

signed: N.M.Mulders

drawing number: A4

units: mm

format: A4
Appendix T  Design

The results of the muscle activation experiment indicated that the pulling forces as encountered in windsurfing could be resisted with decreased muscle activation with the experimental prototype, even though the cause of forearm discomfort for glove-wearing windsurfers was not discovered. A preliminary design has been made based on the way the prototype in the experiment attached to the forearm. The manner the prototype attached to the boom is not viable for real windsurfing and needs to be redesigned. In this appendix the criteria for such a design are discussed, and a preliminary design is presented.

T.1 Engagement and disengagement to the boom

During windsurfing, sailors unhook their waist harness for two main reasons. The first reason is that they need to be able to release the boom, for example just prior to jumping. Unhooking the waist harness allows them to let go of the boom in case something goes wrong during the jump. It also allows sailors to let go in preparation of jibing or tacking, and switch to the other side of the sail. The result is that the sailor will fall into the water free of the windsurfing equipment, so he is less likely to injure himself or damage his equipment. The second reason is that an engaged waist harness limits the range of motion of the sail, relative to the sailor’s body. When sailing in bumpy or gusty conditions, windsurfers often need to make large corrections to prevent a fall. When the waist harness is unhooked, they can make larger corrections to the sail’s position and angle. The situations described above mean that when the forearm, hand and fingers relax (or actively let go), different things should happen in each situation. In the first situation the sailors hands should come off the boom for safety reasons, while in the second situation, the sailor needs to hold on to the boom but merely wants the extra range of motion to prevent a fall. Any design that “connects” to the boom and transfers sail force between arm and boom needs to be able to cope with these two conflicting situations; it basically needs to be able to operate in two distinct modes.

Mode 1 Engaged. Sailor is able to relax and the design transfers force between arm and boom.
Mode 2 Disengaged. When the sailor relaxes, or actively lets go of the boom, the connection should not be maintained for safety.

Sailors should also be able to switch between those modes without taking their hands of the boom, as that would result in reduced control.

T.2 Operating environment

Any design will need to withstand harsh operating conditions: Sand and salt make for abrasive and corrosive conditions, which requires rugged materials. Electromechanical, hydraulic or pneumatic systems could probably be used to facilitate the engagement criteria (Sec. T.1), but if a simple, mechanical solution can be designed it is preferred. A design that does not contain moving mechanical parts would also be preferred, considering the abrasive operating conditions. Materials proven to be insensitive to the corrosive conditions should be used to build the design.

T.3 Adjustability

During the muscle activation experiment, people sometimes requested length adjustments of the boom strap of less than 1 cm. That indicates that people are quite sensitive to the hand posture when holding a boom, as the length of the boom strap determines the hand posture when the boom
strap is taut. Any design should take that experience into account, and make it possible to easily adjust the distance between boom and wrist, in ‘force transfer mode’. In case boom attachments concept is chosen, one can either the boom attachments adjustable, or the brace itself. In that case, it’s better to adjust the brace, because with one adjustment, the boom to wrist distance can be set for both sides of the boom. However, if the boom attachments were made adjustable, one would have to adjust both sides of the boom to the brace, which takes more effort and is thus less user friendly.

T.4 Safety

Windsurfing already is an activity that is inherently risky. Introducing a concept that connects the sailor’s hands to the boom introduces several new safety hazards, that cannot be ignored, and are listed below.

- If the hands are unable to come loose from the boom, it is possible to fall backward and get stuck beneath the sail. If that happens, the worst case scenario is that the sailor is unable to free himself and drowns.
- Sailors are sometimes unlucky enough to fall on the boom. As this is an aluminium tube, that fall in itself is already painful. If a sailor falls on the boom attachments, he could get hurt more, as the force of impact would be distributed over a smaller surface area on the sailor’s body due to the small size of the boom attachments.
- Sailors are sometimes, when sailing with the harness engaged, surprised by a strong wind gust, get pulled forward and crash. That happens because they do not or cannot react fast enough to take appropriate action to prevent a fall. This results in a violent crash, in windsurfing jargon known as a “catapult”, and has been known to break harness lines or even the harness or harness hook itself. If this happens with one or both forearm braces engaged, injury could occur to the sailor’s arms or shoulders.

As these are not the least of hazards, any design need to recognize and address them. Considering the consequences of the first hazard, any design that can conceivable get blocked or jammed (for example sand blocking a mechanism) so that it cannot easily detach from the boom should be discarded. To address the second hazard, the boom attachments should not have sharp edges, and if possible should be made from flexible materials to reduce impact forces. Normally, arms and shoulders are naturally ”protected” from excessive tensile loads, as the hands will simply not be able to hold on the boom. A brace that couples the hands to the boom essentially overrides that inherent safety. A design with a safety release, that decouples itself in case of an excessive tensile load should solve that problem. Preferably, the force at which the device releases is adjustable, to suit a sailor’s individual needs and preferences. A reusable safety release is also preferable to one that can be used only once, as sailors then don’t have to stop sailing or replace components, in case the safety release decouples.

T.5 Strength

Peak harness line forces were measured to be roughly 1.5 times the body weight by Walls and Gale (2001). Sailors will most likely be able absorb shocks much better when not using the harness, as they can use their knees and elbows to dampen the shocks. Peak forces on the arms and hands will most likely be lower than 1.5 times the body weight, with the harness disengaged. In case of equal load distribution, peak force per hand should not exceed 0.75 times the body weight. It must be noted that Walls and Gale did their measurements on flat water and did not include the
forces resulting from jumps and waves. However, if all force is transferred through the design, the intended safety release should decouple, but other components should not break first. Assuming a maximum body weight of 100 kg, the minimum tensile strength should be 200 kg (735.75 N)

T.6 Design criteria

Based on the reasoning in sections T.1 - T.5, a summary of the criteria a successful design should fulfill is given in the Table T.6.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two operating modes</td>
<td>One mode to allow force transfer, one mode to be able to let go of boom if needed</td>
<td>-</td>
</tr>
<tr>
<td>Mode switching</td>
<td>People should be able to switch between operating modes, while maintaining grip on the boom</td>
<td>-</td>
</tr>
<tr>
<td>Adjustability</td>
<td>Distance between brace and boom should be adjustable</td>
<td>-</td>
</tr>
<tr>
<td>Safety I</td>
<td>It should be impossible to get stuck in force transfer mode</td>
<td>-</td>
</tr>
<tr>
<td>Safety II</td>
<td>Boom attachments should not have sharp edges and be made of flexible materials</td>
<td>-</td>
</tr>
<tr>
<td>Safety III</td>
<td>Design should decouple from the boom in case tensile forces exceed 75 kg</td>
<td>75 kg</td>
</tr>
<tr>
<td>Strength</td>
<td>The other components should be strong enough to hold a tensile force of 75 kg</td>
<td>75 kg</td>
</tr>
<tr>
<td>Materials</td>
<td>Any materials used should be insensitive to the abrasive and corrosive operating conditions</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6: Criteria for the design of a windsurfing forearm brace

T.7 Design results

Assuming a forearm brace is used, there are roughly two options to connect to the boom.

**Option 1** Have a component attached to the brace shaped such that it is able to transfer force from the boom’s circular profile to the arm.

**Option 2** Extra component on fixed to the boom, which is designed to engage to a component on the brace.

The first option’s main benefits are that no extra components on the boom are necessary, and that a design using this can connect to any location on the boom. Its drawbacks are that a big and (relatively) heavy component is attached to the arm. Meeting the criteria mentioned in Sec. T.1 will not be easy with such big component without moving parts.

The second option’s main benefit is that one can use a very small and lightweight component on the arm, as a dedicated boom attachment allows more design freedom. In case of emergency, a small and lightweight forearm attachment will be less of a hindrance than a bigger, heavier attachment, meaning swimming is easier and less tiring. The drawbacks of dedicated boom attachments are that four extra components are necessary (two on each side of the boom), and that the design can only engage at the locations of the boom attachments. This drawback however introduces that, if the sailor simply grabs a different location on the boom, he has essentially switched between the modes described in Sec. T.1. If smartly designed, no moving parts are required to (dis-)engage, which
instantly makes it much easier to design a brace that is able to operate in the harsh conditions. Because of the benefits of the boom attachment type solution, this solution was chosen for the preliminary design. Figure 47 shows the modified experiment prototype, where the strap that used to loop around the boom is now looped through a slot in stainless steel hook. This hook has two additional slots, which are used to attach another strap to it. That strap is placed around the hand and ensures the hook maintains its position. On the boom, there is now an extra component, basically a flexible loop, very similar to a harness line. The loop is oriented away from the sail, in the direction of the sailor.

Figure 47: Modified experiment prototype (right) and boom attachment (left)

The hook can engage the loop (Fig. 48), while the sailor places his fingers on the boom attachment. Just like regular harness lines, a flexible but tough protective plastic tube covers the rope material, to reduce wear from the metal hook sliding on it. Unlike regular harness lines, the loop is oriented vertically. This allows sailors to engage and disengage it from the side. The opening of the hook is on the thumb side of the hand, meaning the Fig. 48 shows a design intended for the left hand.
T.8 Evaluation of criteria

The design is able to operate in the two intended modes; the mode it is in is dependent on where the sailor holds the boom.
The way sailors switch between these modes has not yet been tested. Switching between modes requires subtle and coordinated movements of the wrist, hand and fingers. Tests will need to show whether or not users are able to engage and disengage the design from the boom attachments.
The distance of the hook to the brace can be set using the brace's buckle. As this distance partly determines the distance between boom and brace in force transfer mode, the adjustability criterion is met. The hook is much bigger than the loop, so it is unlikely that under normal conditions the hook gets stuck in the boom attachment loop.
There are no mechanisms present that could lock up due to sand or salt build-up. An extraordinary situation could occur where only one out of two wrist designs stays engaged, and the sailor rotates in relation to the boom. This could potentially tighten the loop around the hook making it hard for the hook to slide out of the loop. In the unlikely scenario that this occurs, the sailor will have his other hand free, as he would not be able to rotate relative to the boom otherwise. The sailor can then use his free hand to undo the brace's tightening straps and remove the brace from his arm.
All boom attachments are made from flexible materials, reducing the likelihood of the sailor hurting
himself on them to the likelihood of hurting himself on harness lines.
No provision has been made to protect the sailor from excess pulling force.
No physical prototype has been made of the design, so no tests have been done to determine its strength.
As the main materials such as nylon straps, velcro and stainless steel are also successfully used to manufacture harness and harness hook, the design should be rugged enough to operate in the harsh conditions. A summary of this evaluation is given in Table

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Criterion met?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two operating modes</td>
<td>Yes</td>
</tr>
<tr>
<td>Mode switching</td>
<td>?</td>
</tr>
<tr>
<td>Adjustability</td>
<td>Yes</td>
</tr>
<tr>
<td>Safety I</td>
<td>Yes/(?)</td>
</tr>
<tr>
<td>Safety II</td>
<td>Yes</td>
</tr>
<tr>
<td>Safety III</td>
<td>No</td>
</tr>
<tr>
<td>Strength</td>
<td>?</td>
</tr>
<tr>
<td>Materials</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 7: Table showing whether the criteria were met or not. A question mark (?) indicates that the design takes that criterion into account but needs testing to be sure about it.

T.9 Recommendations for future design

Even though it seems unlikely that the hook can get stuck in the loop when rotated several times, a potentially very dangerous situation for the sailor can develop, if he gets stuck under the sail unable to breathe. In light of that, it is recommended that testing is done, to be certain. Redesigning the hook so its diameter gets smaller towards the end of the hook should also reduce the chances of it getting stuck. Just in case it does happen, a quick release should reduce the time it takes a sailor to take the brace off his arm. This could be done by connecting the ends of the tightening straps together, so that the sailor can undo all straps in a single motion.

Further testing should determine whether or not people can switch between the two operating modes, without letting go of the boom.

Dimensions of the various components should be evaluated to see if they meet the strength criterion. Once that has been done, a prototype should be made and tested for strength.

An addition provision should be made, ensuring the design decouples from the boom in case of excessive tensile load to protect the sailor. This can be integrated within the hook, but also in the strap that loops through the hook, or within the boom attachment.
Appendix U  HREC application forms

This appendix, spanning the next 10 pages, contains the documents sent to the Human Research Ethical Committee to apply for approval of the experiment. As the actuator used in the experiment was not have CE-certified, and no safety expert had inspected the actuator and certified its safety, the approval from the Ethical committee was more than just a formality. This appendix contains the checklist and application forms for the HREC application and an appendix describing the safety measures taken to ensure subject safety during the experiments. A letter of approval by the HREC committee was received on Dec 2nd, 2013. As this was a confidential letter it is not included in this report.

Please note that any references to Appendix A within this Appendix (U) refer to the appendix included in the HREC application.
Research Ethics Application

Please fill in the checklist first if you have not done so already. Please complete this form digitally and send it the Ethics Committee.

Date of Submission: 22-10-2013

Project Title: Design and validation of a cold weather windsurfing hand orthosis

Name(s) of researcher(s): Nigel Mulders

Name of supervisor (if applicable): Dr. ir. Arjo Loeve, dr.ir. Winfred Mugge, dr.ir. Gabrielle Tuijthof

Contact Information

Department: Biomechanical Design, Mechanical engineering

Telephone number: +31614041157

E-mail address: n.m.mulders@student.tudelft.nl

Contact information of external partners (if applicable): N/A

Research

R.1. What is the research question? Please indicate what scientific contributions you expect from the research.
To reduce forearm muscle fatigue a novel cold weather windsurfing hand-brace was designed. In order to validate the new hand-brace design Electromyographic (EMG) measurements will be performed while subjects interact with an actuator to mimic dynamic forces encountered during windsurfing.

R.2. What will the research conducted be a part of?
☐ Bachelor’s thesis
☒ Master’s thesis
☐ PhD thesis
☐ Research skills training
Other, namely: Enter what the research is part of here.

R.3. What type of research is involved?
☐ Questionnaire
☐ Observation
☒ Experiment
Other, namely: Enter the type of research here.

R.4. Where will the research be conducted?
☐ Online
☒ At the university
☐ Off-campus / non-university setting: Enter which setting here.
Other, namely: Enter where the research will be conducted here.

R.5. On what type of variable is the research based?
Give a general indication, such as a questionnaire scores, performance on tasks, etc.
Muscle activation levels will be recorded using surface EMG measurements in lab-recreated wind surfing conditions, using an actuator to mimic dynamic forces encountered during wind surfing. Three different conditions will be compared: bare hand, gloved hand and with the new hand-brace.

**R.6. If the research is experimental, what is the nature of the experimental manipulation?**
Subjects are holding a wind surfing bar and pull at a force level comparable to wind surfing (~200 N). Passive springs counteract this force for the larger part (~125 N), and a hydraulic, force-controlled piston slightly varies (ranging between 0-150 N) the pulling force to mimic wind gusts and waves as come across during wind surfing. The subjects try to maintain the same position of the bar by slightly adjusting their pulling force. This task will be completed with and without wind surfing gloves, as well as with gloves and the new device.

**R.7. Why is the research socially important? What benefits may result from the study?**
The new design could reduce muscle fatigue during wind surfing, which is especially important in cold weather conditions.

**R.8. Are any external partners involved in the experiment? If so, please name them and describe the way they are involved in the experiment.**
No

**Participants**

**Pa.1. What is the number of participants needed? Please specify a minimum and maximum.**
Minimum: 10
Maximum: 20

**Pa.2.a. Does the study involve participants who are particularly vulnerable or unable to give informed consent?** (e.g., children, people with learning difficulties, patients, people receiving counselling, people living in care or nursing homes, people recruited through self-help groups)
No

**Pa.2.b. If yes and unable to give informed consent, has permission been received from caretakers/parents?**
N/A

**Pa.3. Will the participants (or legal guardian) give written permission for the research with an 'Informed Consent' form that states the nature of the research, its duration, the risk, and any difficulties involved? If no, please explain.**
Yes

**Pa.4. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children or students)? If yes, please explain.**
No

**Pa.5. How much time in total (maximum) will a participant have to spend on the activities of the study?**
Maximum of two hours

**Pa.6. Will the participants have to take part in multiple sessions? Please specify how many and how long each session will take.**
No, one session

**Pa.7. What will the participants be asked to do?**
Subjects are asked to keep a bar in their right hand at a constant position by leaning backward with a stretched right arm. Visual feedback on the bar position is provided on a monitor in front of the subject. Muscle activation levels in the forearm are measured using surface EMG electrodes.

**Pa.8. Will participants be instructed to act differently than normal or be subject to certain actions which are not normal?** (e.g. subject to stress inducing methods)
No
Pa.9. What are the possible (reasonably foreseeable) risks for the participants? Please list the possible harms if any.

High unexpected forces could occur in case of actuator malfunctioning. Subjects could lose balance and fall.

Pa.10. Will extra precautions be taken to protect the participants? If yes, please explain.

The human have to pull to the actuator via the wind surfing bar. The actuator is coupled to the wind surfing bar via a cable and a magnetic safety coupling; this magnetic coupling is designed and tested to decouple at a tensile force of \(\approx 370\) N. The actuator has a stroke of 40 cm and the actuator controller exits and overrides any control input if force levels of over 200N are measured. The cable between handhold and actuator has a length of 1.5 m, so the subjects are at no point before, during or after the experiment within the physical range of the actuator with any part of their body. No objects are nearby the subject could fall into. In case the subject falls backwards, a mattress on the floor will ensure he does not harm himself. Pictures and more details of the experimental setup can be found in Appendix A.

Pa.11. Are there any positive consequences for a participant by taking part in the research? If yes, please explain.

No

Pa.12. Will the participants (or their parents/primary caretakers) be fully informed about the nature of the study? If no, please explain why and state if they will receive all information after participating.

Yes

Pa.13. Will it be made clear to the participants that they can withdraw their cooperation at any time?

Yes

Pa.14. Where can participants go with their questions about the research and how are they notified of this?

They can contact Nigel Mulders or dr. ir. G. Tuijthof, and are notified of this through their consent form

Pa.15. Will the participants receive a reward?

☐ Travel expenses
☐ Compensation per hour
☒ Nothing

Other, namely: Enter the reward here.

Pa.16. How will participants be recruited?

As experienced windsurfers are required, a windsurfing student association will be approached to recruit participants

Privacy

Pr.1. Are the research data made anonymous? If no, please explain.

Yes

Pr.2. Will directly identifiable data (such as name, address, telephone number, and so on) be kept longer than 6 months? If yes, will the participants give written permission to store their information for longer than 6 months?

No

Pr.3. Who will have access to the data which will be collected?

Only the researcher (Nigel Mulders) and his supervisors (dr. ir. W. Mugge, dr.ir A Loeve, dr. ir. G. Tuijthof).

Pr.4. Will the participants have access to their own data? If no, please explain.

No, not directly. To maintain the overview the data is only accessible for the people mentioned in question Pr. 3. However, if people wish to access their data they can receive a copy of only their own data from the researcher.

Pr.5. Will covert methods be used? *(e.g. participants are filmed without them knowing)*

No
Pr.6. Will any human tissue and/or biological samples be collected? *(e.g. urine)*
No

Documents

Please attach the following documents to the application:

- Text used for ads (to find participants);
- Text used for debriefings;
- Form of informed consent for participants;
- Form of consent for other agencies when the research is conducted at a location (such as a hospital or school).
Research Ethics Checklist

1. Complete this checklist before you start your research study.

2. Send/give the completed and signed form to the Human Research Ethics Committee
   HREC@tudelft.nl

3. Keep a copy for your records.

**Important note concerning question 1**

Note that research involving participants who are in a dependent or unequal relationship with
the researcher or research supervisor (e.g., the researcher’s or research supervisor’s students
or staff) may be regarded as a vulnerable group.¹ If your study involves such participants, it is
essential that you safeguard against possible adverse consequences of this situation (e.g.,
allowing a student’s failure to complete their participation to your satisfaction to affect your
evaluation of their coursework). This can be achieved by ensuring that participants remain
anonymous to the individuals concerned (e.g., you do not seek names of students taking part
in your study). If such safeguards are in place, or the research does not involve other
potentially vulnerable groups or individuals unable to give informed consent, it is appropriate
to check the NO box for question 1.

¹ Children, mentally challenged, historically discriminated-against, etc.
This checklist should be completed for every research study that involves human participants. Before completing it please refer to the Central Committee on Research Involving Human Subjects (CCMO) http://www.ccmo-online.nl/main.asp?pid=1&taal=1 This checklist must be completed fully and submitted before potential participants are approached to take part in your research study.

**Project title: Design and validation of a cold weather windsurfing hand orthosis**

**Name(s) of researcher(s): Nigel Mulders**

**Name of supervisor (if applicable): dr.ir. A. Loeve, dr.ir. W. Mugge, dr.ir. G. Tuijthof**

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Does the study involve participants who are particularly vulnerable or unable to give informed consent? (e.g., children, people with learning difficulties, patients, people receiving counselling, people living in care or nursing homes, people recruited through self-help groups)</td>
<td>☐</td>
<td>■</td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places)</td>
<td>☐</td>
<td>■</td>
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<td>3.</td>
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<td>Will the study involve actively deceiving the participants? (e.g., will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study)</td>
<td>☐</td>
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<td>4.</td>
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<td>Will the study involve discussion or collection of information on sensitive topics? (e.g., sexual activity, drug use, mental health)</td>
<td>☐</td>
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<td>5.</td>
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<td>Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants?</td>
<td>☐</td>
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<td>6.</td>
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<td>Will blood or tissue samples be obtained from participants?</td>
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<td>Is pain or more than mild discomfort likely to result from the study?</td>
<td>☐</td>
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<td>Does the study risk causing psychological stress or anxiety or other harm or negative consequences beyond that normally encountered by the participants in their life outside research?</td>
<td>☐</td>
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<td>9.</td>
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<td>Will financial inducement (other than reasonable expenses and compensation for time) be offered to participants?</td>
<td>☐</td>
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<td>10.</td>
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<td>Will the study involve recruitment of patients or staff through the TU Delft, or working at a TU Delft site?</td>
<td>☐</td>
<td>■</td>
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<td>11.</td>
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<td>Will the experiment collect and store videos, pictures, or other identifiable data of human subjects?</td>
<td>☐</td>
<td>■</td>
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<td>If &quot;yes&quot;, you have to ensure that collected data is safeguarded physically and will not be accessible to anyone outside the study. Furthermore, the data has to be de-identified if possible and has to be destroyed after a scientifically appropriate period of time.</td>
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</tbody>
</table>
12. Will the experiment involve the use of devices that are not “CE” certified?
   a. No [ ] [x]  
   b. If “yes”, was the device built in-house?
      i. No [ ] [x]  
      ii. If “yes”, was it inspected and certified safe by a safety expert at TU Delft? (please provide records of the inspection) [ ] [x]  
      iii. If “no”, was it inspected by some other, qualified authority in safety and approved? (please provide records of the inspection) [ ] [x]  

13. Has or will this research be submitted to a research ethics committee other than this one? (if so, please provide details)
   Name of Committee: [ ]
   Date of submission: [ ]
   Submission or approval number (if known): [ ]

If you have answered NO to all questions above (excluding sub-questions) above (i.e., a more detailed submission to an ethics committee is not required), please very briefly (100-200 words) summarise your research, stating the question for the research, who will participate, the number of participants to be tested and the methods to be used.

Write or type your summary here:

A new cold weather windsurfing hand brace was designed to reduce forearm muscle fatigue. In this experiment we will validate if the new hand-brace results in lower muscle activity. Muscle activation levels will be recorded using surface EMG measurements in lab-recreated windsurfing conditions, using an actuator to mimic dynamic forces encountered during windsurfing. Subjects are holding a windsurfing bar and pull at a force level comparable to windsurfing (average ~200 N, maximum 270 N). Passive springs counteract this force for the larger part (~125 N), and a hydraulic, force-controlled piston slightly varies (ranging between 0-150 N) the pulling force to mimic wind gusts and waves as come across during wind surfing. The subjects try to maintain the same position of the bar by slightly adjusting their pulling force. This task will be completed with and without windsurfing gloves, as well as with gloves and the new device.
Send the completed and signed form to dr. David Koepsell, Chair, Human Research Ethics Committee: HREC@tudelft.nl, TBM-Faculty, Values and Technology, 5 Jaffalaan rm. B4.250

If you have answered ‘NO’ to all questions you can proceed with your study.

If you have answered ‘YES’ to any of the questions above, you will need to submit an application for ethics approval, including sample consent documents to this committee.

To submit your research proposal for consideration by the Human Subjects Research Ethics Committee, use the ethics approval application form available on Blackboard. This Committee meets monthly during term time, and less frequently out of term time.

Signature(s) of researcher(s)

Date:

Signature research supervisor (if applicable):

Date:
Appendix A: Experimental setup and safety precautions.

A custom setup has been designed and manufactured to perform the experiment. The total force on the handhold (which the subject experiences), is the sum of actuator force and spring force (Fig 1). The springs run parallel to the actuator are pre-tensioned by the subject prior to the experiment. Below, the most important components are listed.

1: Hydraulic actuator
2: Springs
3: Spring cable
4: Handhold
5: Safety breaking rod
6: Magnetic safety coupling
7: Cable between handhold and actuator (L=1.5 m)
8: Force sensor

The actuator software does not allow the actuator to exert a force higher than 200N. Combined with a spring force, the setup is capable of a maximum total pulling force of ~350N with the springs at the maximum length (corresponding to the maximum stroke of the actuator.) As this is less than half the body weight of the intended subjects this is a safe force level. A pushing force cannot be exerted on the handhold as the handhold is connected to the actuator by a 1.5m cable. In the experiments, a maximum force of 270N will be experienced by the subjects. In the unlikely case the software or hardware controlling the actuator fails, a sudden high force could potentially be exerted.
To protect the subject from possible injury in this unlikely scenario, a magnetic safety coupling has been incorporated. Three separate measurements on the coupling were done which showed maximum forces: 371.2N, 368.8N and 368.2N. This repeatability shows that it is highly unlikely that the force the magnetic coupling can transfer is any higher than 375N. This is still a safe force level. In case the coupling releases, it is possible that the subject falls backwards. For safety reasons, there will be a mattress there to prevent injury. It must be noted that because of his stable position on his knees, it is unlikely that the subject will actually fall over if the magnetic coupling disengages.

Figure 5: Magnetic coupling assembled (R) and disassembled (L)