Forearm fatigue during grinding and development of grinder- specific handle

Master's Thesis

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Synopsis:

This study aimed to investigate forearm fatigue during grinding and methods to decrease this with handle design. The present master thesis is divided into three articles. The literature regarding this topic is limited and in order to present aim and goals clear it was it necessary to divide it into three articles.

Each article has its own aim, yet all three build upon each other. Study one purpose: Understanding the influence of grinding direction on forearm fatigue. Study two purpose: Tests different handle diameters grinding backwards. Study 3 purpose: A technical note explaining how to develop custom-fitted handles for individuals.

Forearm fatigue is measured using time to fatigue, maximum voluntary contraction and surface electromyography for all three studies.

Study one found indications of forearm fatigue being more severe during backwards grinding than forward grinding. These indications are based on statistically significant difference in time to fatigue and MVC. In addition, sEMG shows the same signs but nothing of statistical significance. Preceding with newfound knowledge from study one 'the optimal handle diameter' is established in study two. The optimal handle diameter (32 mm) is based solely on backwards grinding. The 32 mm handle results in less forearm fatigue in relation to time to fatigue and MVC. Finally, study three (technical note) is a description of method to custom-fit individualized handles using 3D scanning and printing. Study one and two as well as related grip strength studies work as the foundation for the developed method in the technical note.

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Preface

This master thesis is divided into three articles and one set of work sheets. One main topic, *forearm fatigue during grinding*, is present in all three articles. The literature regarding this topic is limited and in order to present aim and goals clear it was it necessary to divide it into three articles.

Observations have shown that grinders suffer from premature forearm fatigue. Forearm fatigue, can in some cases lead to injury, this connection has been found in other upper body sports such as rowing (Rumball et al. 2005; Karlson 2012)*. These forearm injuries also appear in grinding (Allan 1999; Allen 2000; Neville et al. 2006; Neville & Folland 2009) and can as such be decrease with reduced forearm fatigue. A solution for reducing forearm fatigue could be designing new handles for the grinder (Neville & Folland 2009). This is a promising solution since handle diameter affects motor unit recruitment (Fioranelli & Lee 2008) and thereby influence muscle fatigue.

Each article has its own aim, yet all three build upon each other. Study 1 is aiming at understanding the influence of grinding direction on forearm fatigue. Study 2 tests different handle diameter when grinding in only the most important direction found in study 1. Study 3 is a technical note explaining how to develop custom-fitted handles for individuals, based upon newfound knowledge from study 2. The work sheets contain additional materials for all three articles (e.g. background theory, pilot study, method, protocols and additional data).

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Forearm muscle fatigue during forward and backwards grinding

Morten B Simonsen & Anders R Jensen

Abstract

The aim of this study was to investigate the influence of forward and backward grinding on forearm fatigue. Eight subjects participated in this randomized crossover study. The subjects performed both forwards and backwards grinding at a fixed load until a cadence of 120 RPM no longer could be maintained, on separate days. Subjects maximal grip force was measured with a hand-dynamometer before (baseline) and after grinding (post). Additionally was median power frequency of surface electromyography (sEMG) analyzed during grinding on extensor carpi radialis longus and flexor carpi ulnaris. Results showed that time to fatigue was longer during forward grinding (127.4 ± 39.0 s) compared with backwards (92.0 ± 29.2 s), accessed by paired t-test, $t(7) = 2.451$, $P=0.04$. Reduction in post grip force test showed a larger drop in grip force relative to baseline after backwards grinding (84.3 ± 5.1 %) compared with forward (91.9 ± 4.6 %), accessed by paired t-test, $t(7) = 2.351$, $P=0.05$. Implying that backwards grinding is more fatiguing, despite shorter grinding time. No statistical difference was found between median frequencies between the two directions.

Keyword: Grip force, Muscle fatigue, America's Cup

Introduction

Americas Cup (Auld Mug) is a trophy rewarded to the winner of the Americas Cup, which is considered sailing formula 1. Americas Cup trophy is the oldest international sporting trophy and the first race was in 1851 (1,2)**.** The crew consists of six people in the 2017 edition with different tasks (e.g. Skipper, tactician, trimmer, grinders.). The grinders has the most physical demanding task onboard, which is to generate pressure in the hydraulic system (3). The grinders generate the pressure by hand cycle at the grinder pedestal. The hydraulic system controls the sails, and daggerboards. Stored energy and motors are against the rules hence grinding is a continuous task (1,2)**.** A grinding pedestal is constructed as a tandem system with two people standing face to face. This results in one grinding forwards and the other grinding backwards. Pearson et al.(4) have already explored physiological aspect of grinding directions investigating kinematics and muscle activation patterns in relation to torque. Pearson et al.(4) found that grinding directions differed considerably in overall mechanics. Suggesting that both directions should be to trained specifically to improve performance. However, more detailed muscle work has not been investigated in respect to the grinding directions.

Other upper body sports such as rowing or kayaking have athletes experiencing forearm injuries caused by fatigue (5,6). Also mentioned in a review of Neville and Folland (7) , forearm injuries was in top five among grinders (7–9)**.** The prolonged isometric contraction seems to be the problem. It has also been observed that Grinders have problems with premature forearm fatigue. Forearm fatigue and its relation with grinding directions have not been investigated to the author's knowledge. Grinders in the America's Cup both push and pull when they are grinding. Backwards grinding have been associated with a pulling exercise and forwards with pushing exercises to predict grinding performance (3)**.**

The aim of this study is to investigating forearm fatigue, between forward and backwards grinding.

Material and method

Subjects

Eight healthy male subjects, with no history of hand, wrist or arm problems were recruited for this experiment. Mean ± SD age, height and body mass of the subjects were 24.5 ± 1.6 yr, 183.1 ± 6.1 cm and 78.8 ± 12.2 kg, respectively.

Experimental design

The experiment took place at Aalborg University, Denmark, as a randomized cross over study. The experiment consisted of two trials with each grinding direction. Tests were placed on separated days with 24 to 48 hours between trials.

Procedures

The subjects' demographic data was collected. Surface electromyography (sEMG) sensors were placed on muscles involved in flexion or extension of the wrist as well as gripping(10)**.** Extensor carpi radialis longus (ECR) and flexor carpi ulnaris (FCU) was found by using palpation techniques. After the electrodes were placed on subjects, a 5-minute familiarization and warm-up on the grinder began. 2 minutes after the warm-up the subjects' baseline grip strength was measured with a Maximal voluntary contraction test (MVC). Subjects performed MVC for 3 seconds on a hand dynamometer (G200 Model, Biometric Ltd., Newport, UK). MVC was repeated three times followed by 2 minutes breaks after each trial. After the last MVC break, the subjects started grinding with a fixed torque of 10 Nm with cadence of 120 rpm (126W). The test stopped when subjects no longer could maintain the cadence of 120 rpm, the time on the grinder was noted, and this is defined as time to fatigue. Time was blinded during trials. A post MVC test was performed immediately after grinding. The grinder pedestal is a custom build grinding ergometer, similar setup as reported in Olesen et al.(2)**.**

Surface electromyography data collection

Before placement of sEMG electrodes the skin was prepared by removing all hair and cleaning with a gel on the skin. sEMG sensors (Neuroline 720, Ambu, Denmark) was placed on the muscle belly of ECR and FCU using a bipolar setup. Identifying muscles location using palpation techniques, flexing and extending the wrist or closing and opening the hand (11). The sensors were placed on the longitudinal axial of the muscle. Gain was set to 2000 and a sample rate to 2000 Hz.

Signal processing

sEMG signals were digitally band-pass filtered (third order Butterworth filter) between 20-400 Hz. The signal was transferred from time domain to frequency domain through a short-time Fourier transform using a window length of 10 seconds with 50% overlap in MATLAB® (Mathworks, Massachusetts, USA). The first and last 5 seconds of sEMG signal was excluded from analyses to ensure that analyzed data was collected while subjects were grinding with the right cadence. Median frequency (MF)(12) was calculated for the first and last 20 seconds from the remaining signal.

Statistical method

The level of statistical significance was set at $\alpha < 0.05$. All data was tested for normality using Shapiro Wilk test and data is reported as mean ± SD. Paired-t test was used to determine difference between time to fatigue and MVC. A Two-way ANOVA with repeated measures was used to investigate differences in sEMG mean between grinding directions and muscles. Relative MVC are calculated as (post/baseline*100) and Relative MF are calculated as (end/start*100). SPSS (Version 22; SPSS Inc, Chicago, IL, USA) was used to analyze the data.

Results

Time to fatigue

Time to fatigue was longer during forward grinding (127.4 ± 39.0 s) compared with backwards grinding (92.0 ± 29.2 s). A Paired-t test showed a statistical significant difference between the two grinding directions; t(7) = 2.451, P=0.04. Time to fatigue mean are shown in figure 1 for each direction with SD.

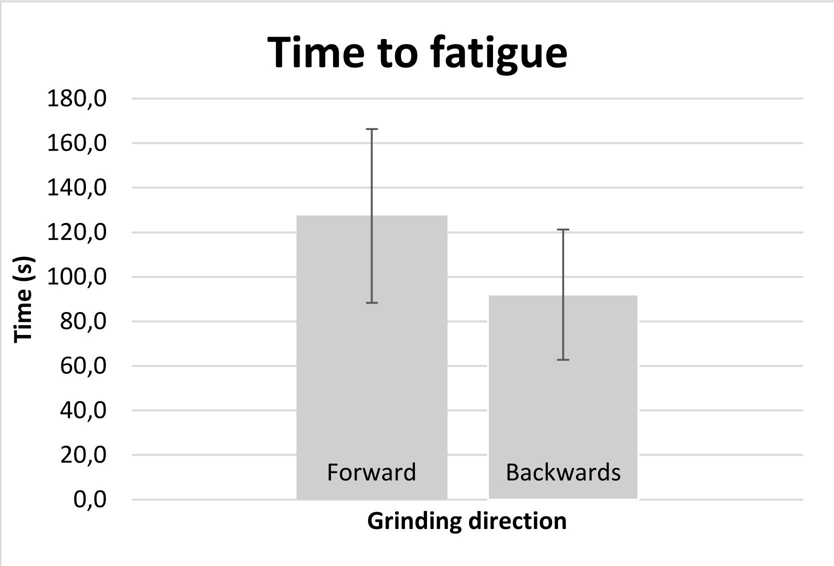

Figure 1 Time to fatigue in different directions scaled in seconds (s).

MVC

Paired t-test showed a statistical difference between baseline and post MVC for both forward and backwards grinding t(7)=4.277, p=0.004, t(7)=5.591, p =0.001 respectively. The difference between baseline and post MVC showed a reduction of MVC for backwards grinding (84.3 ± 5.1 % of baseline MVC) and forward grinding (91.9 ± 4.6 % of baseline MVC). A Paired-t test revealed a statistical significant difference between the two grinding directions; t(7) = 2.351, P=0.05. Figure 2 shows means of relative post MVC to baseline MVC with SD.

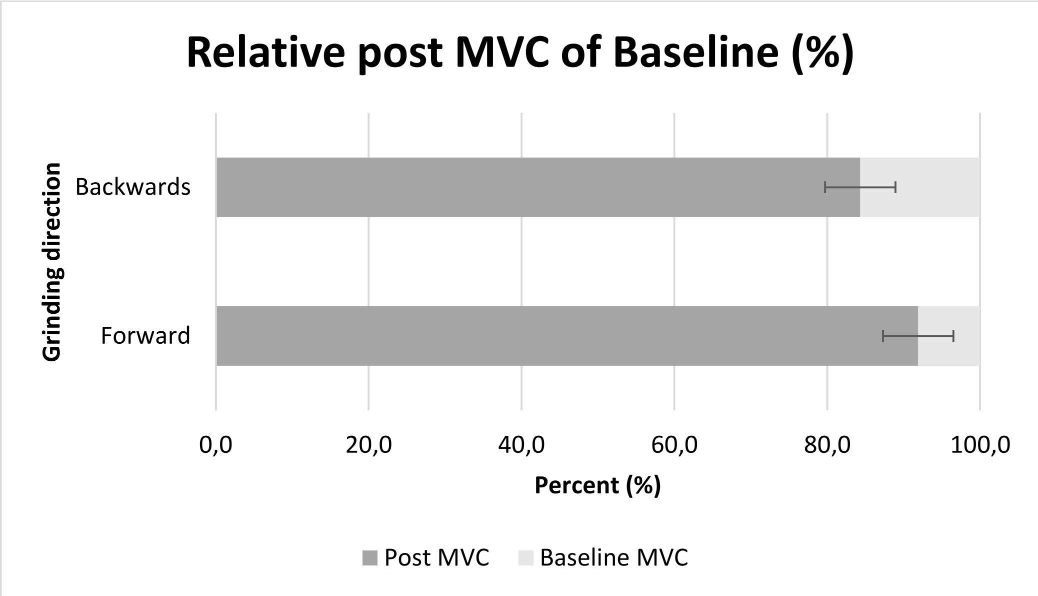

Figure 2 Relative post to MVC of baseline for each direction (Backwards and forward) presented in percent (%).

Electromyography

A 2 x 2 ANOVA with repeated measurements showed a statistical drop in MF between the first 20s until the last 20s of forward grinding for both ECR and FC; $F(1,7) = 10.508$, $p = 0.014$, partial $\eta = 0.600$. And backwards grinding; $F(1,7) = 31.675$, $p = 0.001$, partial $\eta = 0.819$. Figure 3 and 4 shows the mean of MF at the end of grinding relative to start of grinding, for ECR and FCU, respectively. A 2 x 2 ANOVA with repeated measures analyze did not show any statistically significant difference between forward (ECR: 93 ± 9 %, FCU: 89±7%) and backwards (ECR: 86 ± 10 %, FCU: 86 ± 9 %) MF; $F(1.2) = 1{,}193$, $P=0.311$.

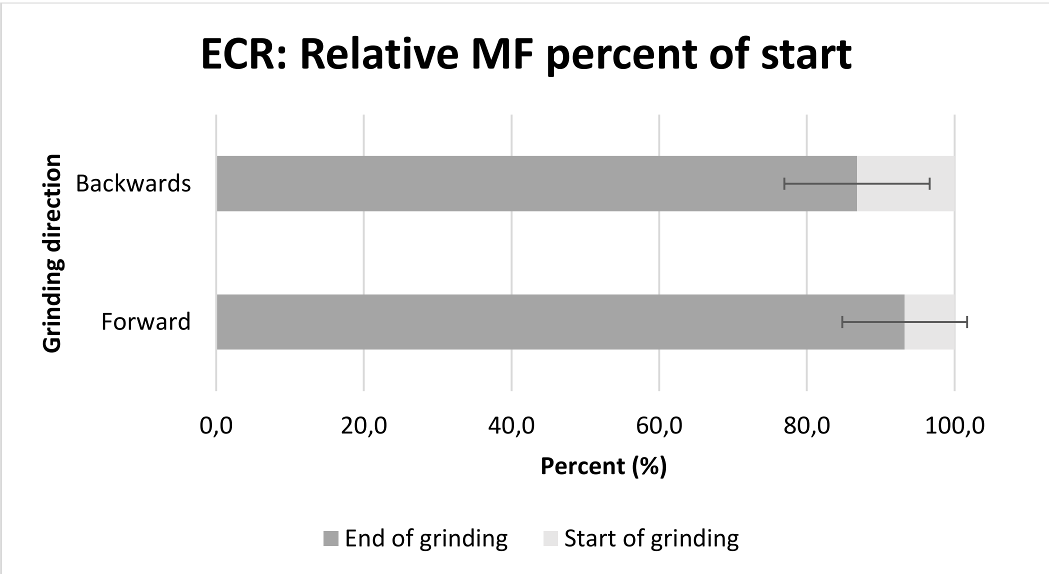

Figure 3 Relative median frequency (MF) for extensor carpi radialis longus (ECR). Both directions showed with the relative difference between end and start of grinding (%) including SD

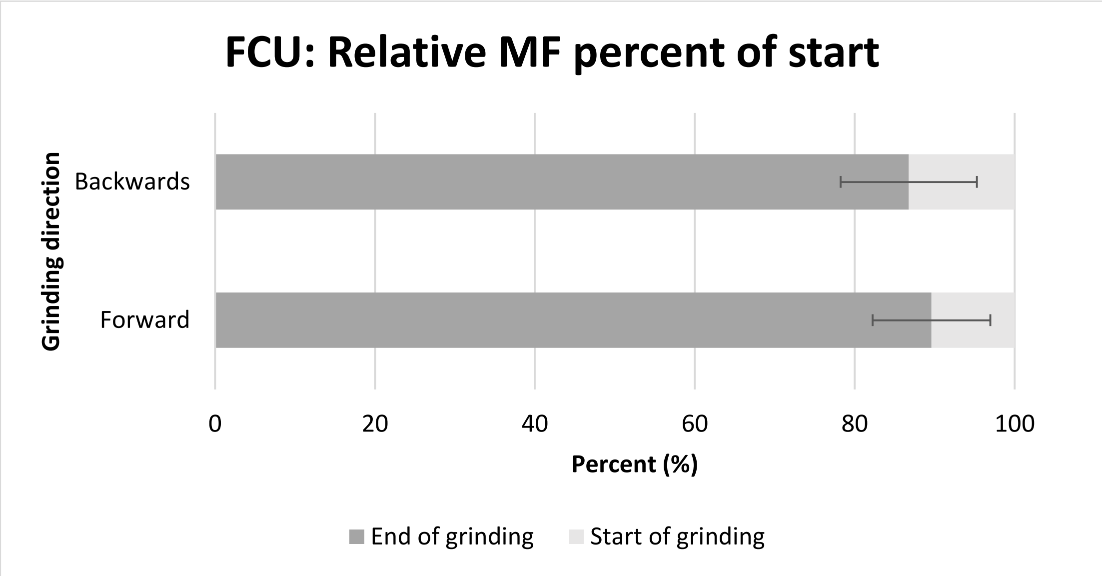

Figure 4 Relative median frequency (MF) for flexor carpi ulnaris (FCU). Both directions showed with the relative difference between end and start of grinding (%) including SD.

Discussion

The results from the present study show a statistical difference in time to fatigue between forward and backwards grinding. Time to fatigue is shorter during backwards grinding compared with forward grinding. The mean time difference is 35.3±40.8s. In addition, there is a decrease from baseline to post MVC, which is statistically significant larger for backwards grinding (84.3 ± 5.1 %) compared with forward grinding (91.9 ± 4.6 %). The results from time to fatigue and drop in MVC indicate that backwards grinding is more fatiguing for the forearm. Despite that, grinding time during backwards grinding is shorter. sEMG data reveals a difference in MF between start and end of grinding for both directions, indicating that forearm muscles are fatiguing during grinding. However the data shows no statistical difference between drops in MF between the two directions. However, the mean drop is larger during backwards (ECR: 86 ± 10 %, FCU: 86 ± 9 %) than forward grinding (ECR: 93 ± 9 %, FCU: 89±7%). However, there is no statistical difference found between directions, this might be due to sample size.

Time to fatigue and MVC show that backwards grinding puts a higher demand on muscles used for griping. The comparison to an earlier study regarding grip strength and endurance during dynamic exercises shows that pulling exercises require a larger muscle fiber recruitment then pushing exercises(13). This grinding study shows the same tendency since grinding directions are comparable to push and pull exercises (3).

All subjects are new to grinding, and have limited experience with the movement, resulting in various techniques during grinding. Some subjects move their entire upper body while grinding, other constantly change foot position during grinding. After each test, some subjects claim that shoulder fatigue is one reason they cannot go on. Being unexperienced is properly equal to poor muscle memory, which can lead to inappropriate coordination and muscle recruitment compared to professionals' grinders (14).

Subjects' cardiovascular system might be another reason for stopping - since most subjects breathe heavily when stepping down from the grinder. The subjects are instructed to grind with a cadence of 120 rpm (126W) until it can no longer be maintained and fatigue is reached: When a muscle can no longer produce the required amount of force to uphold a certain level of activity (10).

The chosen cadence on 120 RPM is based upon Olesen el at.(2) recommendation. It is possible that the relatively high cadence is challenging the subjects' respiratory system rather than muscular system. Smith, Price and Doherty (15) found that the most optimal cadence during arm cranking would be between 70-80 RPM for best physiological response. During biking it has been found that low cadence cycling is more economical from a respiratory point of view than high cadence cycling. For instance, it has been found that lower cadence results in greater muscular fatigue than high cadence(16). Testing with lower cadence and higher resistance would perhaps result in greater forearm fatigue. Nevertheless, the relationship between forearm muscular fatigue and grinding cadence has not yet been investigated. The time to fatigue and MVC results from the present study shows that forearm fatigue during backwards grinding is more critical than forward grinding.

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Handle diameter influence on forearm muscle fatigue during backwards grinding

Morten B Simonsen & Anders R Jensen

Abstract

The aim of this study was to investigate the optimal diameter for backwards grinding. Ten subjects participated in this randomized crossover study. The subjects performed backwards grinding until fatigue at a fixed load with three different cylindrical handles (32mm, 36mm and 40mm in diameter), on separate days. Maximal voluntary contraction (MVC) was measured before (baseline) and after grinding (post). Additionally median power frequency of surface electromyography (sEMG) was analyzed during grinding. Results showed that time to fatigue was longer with the 32mm handle, accessed by Friedman test ($X^2(2)=13.4$, $P=0.001$). No difference was found between 36- and 40 mm. Reduction in MVC from baseline to post was lowest with the 32mm handle, accessed by one-way ANOVA ($F(2.18) = 4.076$, $P= 0,035$, partian $n^2=0.312$). Implying that the 32mm handle is the better option. No statistical difference was found between median frequencies among the three handles.

Keyword: Cylindrical handle, Grip force, Muscle fatigue, America's Cup

Introduction

Americas Cup is considered the pinnacle of yacht racing. The race format is duel based, where two boats race each other on a pre-marked course. All maneuvers on board the boat are performed manually, without assistance from motors or stored energy. The most physically demanding task onboard is grinding (performed by Grinders), where arm cranking is performed to produce pressure in the hydraulic system used for controlling the sails, and daggerboards. Grinders have among the highest numbers of injuries onboard with 3.1 injuries per 1000 hours of sailing, 8-13% and 8-11% of these injuries are related to elbow and forearm injuries during sailing, respectively(1). In other upper body sports like rowing, it has been reported that rowers also have problems with forearm injuries due to improper technique or muscle fatigue(2). Neville and Folland(1) suggest that grinders might benefit from ergonomically optimizing the grinding pedestal, and suggests different handle diameter, custom handle shape and increased grip friction. The optimal handle diameter have been widely investigated, however, only during static contraction (3–6). One thing these studies agree on is that individual hand size play an important role for optimal handle diameter (4,5). Edgren et al.(5) did a static study and found that a handle could not only be too big, but also too small. Subjects performed maximal voluntary contraction (MVC) tests with five different sized cylinder formed hand dynamometer. The diameter of the dynamometers were 25.4 38.1 50.8, 63.5 and 76.2 mm. The results showed that most subject performed highest MVC with the 38 mm handle. This implies that the general optimal size is around 38 mm. In addition, a larger static study involving both sexes showed that an optimal diameter for the general population would be between 20-30 mm (7). Ratamess et al.(8) have tested different weightlifting bars diameter (25.4-, 50.8- and 76.2 mm) during dynamic strength exercises (e.g. pushing and pulling). The results of the experiments showed that the use of bars with larger diameter would result in a lower 1-repetition maximum but only for pulling exercises. This indicates that only exercises where grip strength is of critical importance the size of the bar or the handle matters. Forward and backwards grinding has been associated with pushing and pulling exercises, respectively (9). Results from (Forearm fatigue during Forward & Backwards grinding – Article 1) showed that backwards grinding resulted in reduced grip strength compared to forward grinding. The results supports that backwards grinding is related to pulling exercises and therefore handle diameter on the grinder may influence forearm fatigue.

To the authors knowledge no study regarding handle design during grinding exists. The purpose of this study is to investigate different cylindrical handle diameters influence on forearm fatigue during backward grinding.

Materials and method

Subjects

Ten healthy male subjects, with no history of hand, wrist or arm problems and hand length of 17.5 to 21 cm, were recruited for this experiment. Mean ± SD age, height, body mass and hand lengths of the subjects were 24.6 ± 1.4 yr, 181.3 ± 6.8, 76.5 ± 11.0 kg and 18.6 ± 1.1 cm respectively. The length of the hand was measured from the wrist to the distal end of the middle finger (3).

Experimental design

The experiment was conducted at Aalborg University, Denmark, as a randomized cross over study. The experiment consisted of three trials with three different handle sizes (32, 36 and 40 mm), placed on separated days with at least 24h to a maximum of four days between trials.

Procedures

Demographic data was collected on the first test day. Surface electromyography (sEMG) electrodes (Neuroline 720, Ambu, Denmark) were placed on muscles involved in flexion and extension of the wrist and movement of the fingers (10)**.** The selected muscles were flexor carpi ulnaris (FCU) and extensor carpi radialis longus (ECR). . After the electrodes were placed on subjects, a 5-minute familiarization and warm-up on the grinder began. 2 minutes after the warm-up the subjects' baseline grip strength was measured with a Maximal voluntary contraction test (MVC), where subjects did a 3 seconds MVC test with a hand dynamometer (G200 Model, Biometric Ltd., Newport, UK). MVC was repeated three times followed by 2 minutes break after each trial. After the final MVC, break started subjects grinding with a fixed torque of 10 Nm with cadence of 120 rpm (126 W). The test stopped when subjects no longer could maintain the cadence of 120 rpm, the time on the grinder was noted, this was defined as time to fatigue (10). Time was blinded for subjects. Post MVC test was done immediately after grinding. The grinder pedestal is a custom built grinding ergometer, similar setup as reported in Olesen et al. (11) study.

Electromyography data collection

Before placing of the electrodes the skin was prepared by shaving hair and cleaning of the skin by use of a gel. sEMG electrodes were placed on the muscle belly of extensor carpi radialis longus and flexor carpi ulnaris using a bipolar setup (12)**.** Muscles location was identified by palpation during extension and flexion of the wrist and fingers (13). Gain was set to 2000 and a sample rate was set to 2000 Hz.

Signal processing

sEMG signals were digitally band-pass filtered (third order Butterworth filter) with cut-off frequencies 20-400 Hz. The signal was transferred from time domain to frequency domain through a short-time Fourier transform using a window length of 10 seconds with 50% overlap in MATLAB® (Mathworks, Massachusetts, USA). The first and last 5 seconds of sEMG signal were excluded from analyses to ensure that analyzed data was collected while subjects were grinding. Median frequency (MF) (14) was calculated for the first and last 20 seconds from the remaining signal.

Statistical method

The level of statistical difference was prior set to < 0.05. All data was assessed for normality by Shapiro Wilk test, normally distributed data was presented with mean ± SD, and non-normally distributed data was presented with median (interquartile range). Friedman statistical test was used to compare time to fatigue between the handles and Wilcoxon signed-rank test was used as Post hoc test to detect difference between handles. One-way ANOVA was used to investigate differences between MVC. Two-way ANOVA with repeated measures was performed to investigate difference in sEMG mean between handle diameter and muscles. Bonferroni adjustment was performed as post hoc analysis for all ANOVA test. Relative MVC are calculated as (post/baseline*100) and Relative MF are calculated as (end/start*100). SPSS (Version 22; SPSS Inc, Chicago, IL, USA) was used to analyze the data.

Results

Time to fatigue

Friedman test showed a statistically significant difference between time to fatigue between the handle sizes, $X^2(2)=13.4$, $P=0.001$. Post hoc analysis with Wilcoxon signed-rank test showed a statistical difference between 32mm (91s (83.5 to 108.75s)) and 36mm (81s (69.5 to 108s)) (Z= -2.296, P=0.022) and 32mm and 40mm (81.5s (68.5 to 89.2s)) (Z=-2.805, P=0.005). There was no statistical difference between 36mm and 40mm handles (Z=-1.887, P=0.059). Figure 1 shows a box plot of time to fatigue for each handle diameter.

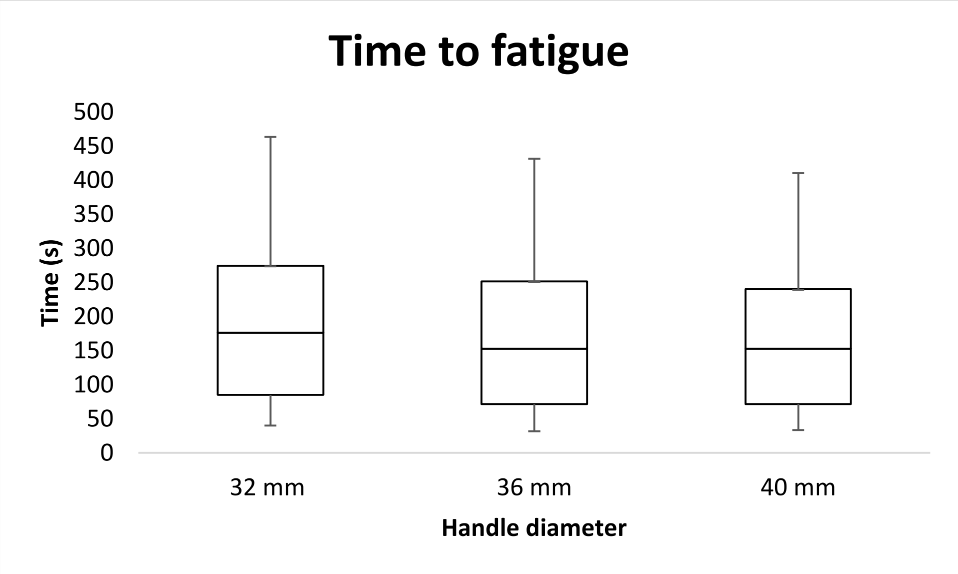

Figure 1 Box plot of time to fatigue for each handle, 32, 36, and 40 mm.

MVC

One way ANOVA with repeated measures showed that post MVC was different from baseline MVC for all handle diameters. 2x2 ANOVA with repeated measures determined that relative MVC drop differed between handle size F(2.18) = 4.076, P= 0,035, partian $n^2=0.312$. Further post hoc test using the Bonferroni correction detected a difference between 32mm and 40 mm (5.1% ± 1.4 standard error, p=0.018). No statistical difference was found between 32mm and 36mm (4.9% ± 2.1 standard error, p=0.137), and 36mm and 40mm (0.02% ± 2.4 standard error, p= 1.0). Figure 2 shows means ± SD for relative reduction in MVC.

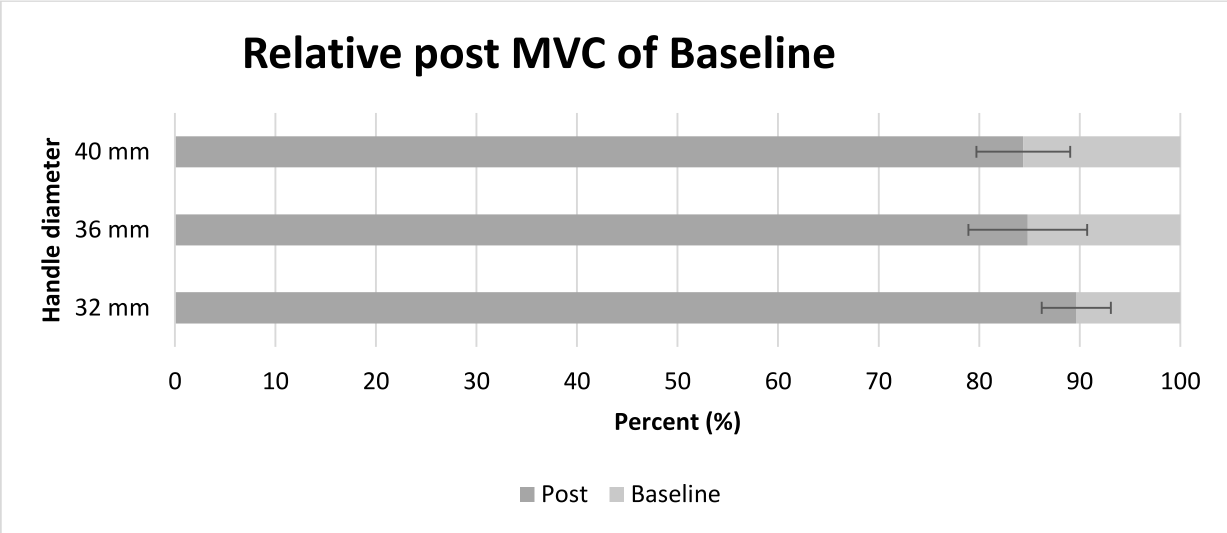

Figure 2 Relative post MVC as a percentage (%) of baseline MVC for each handle size, 32-, 36- and 40 mm.

Electromyography

A two-way ANOVA with repeated measurements showed a statistical drop in MF between the first 20s until the last 20s for all handles for both ECR and FCU; 32 mm ($F(1,9) = 6.389$, $p = 0.032$, partial $\eta = 0.415$), 36 mm ($F(1,9) = 12.927$, $p = 0.006$, partial $\eta = 0.590$), 40mm ($F(1,9) = 6.424$, $p = 0.032$, partial $\eta = 0.416$). Figure 3 and 4 shows the relative frequency drop at the end of grinding relative to the start. Results from a Two-way ANOVA with repeated measurements comparing the relative difference in MF showed no statistically difference between the different handle diameters $F(2,18) = 0.182$, $p = 0.835$.

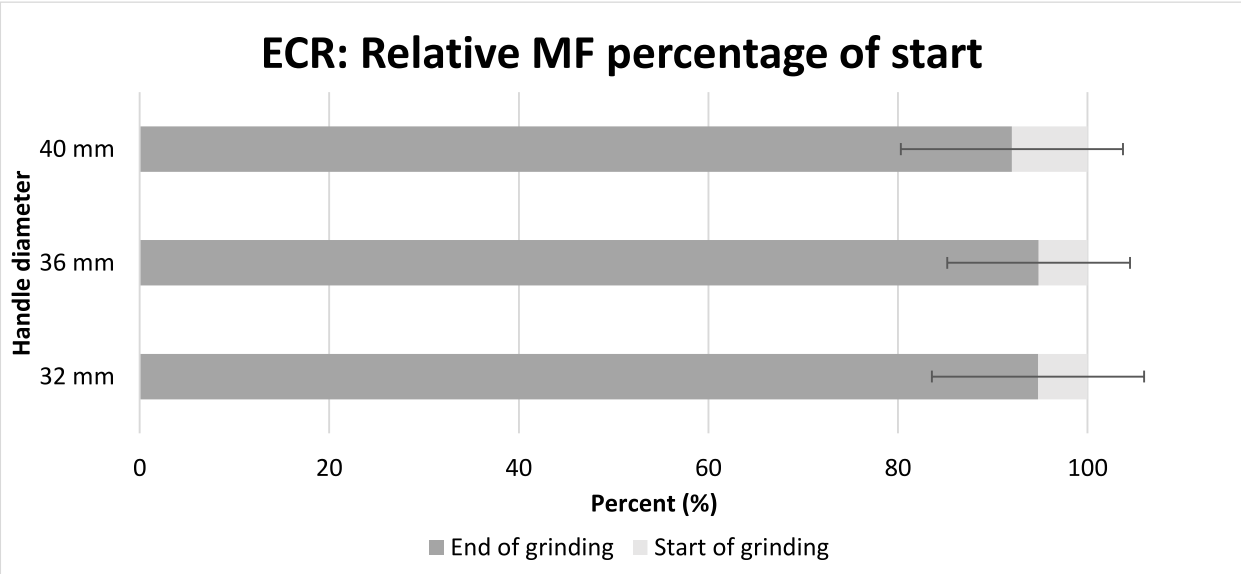

Figure 3 Relative median frequency (MF) as a percentage of start value for extensor carpi radialis longus (ECR).

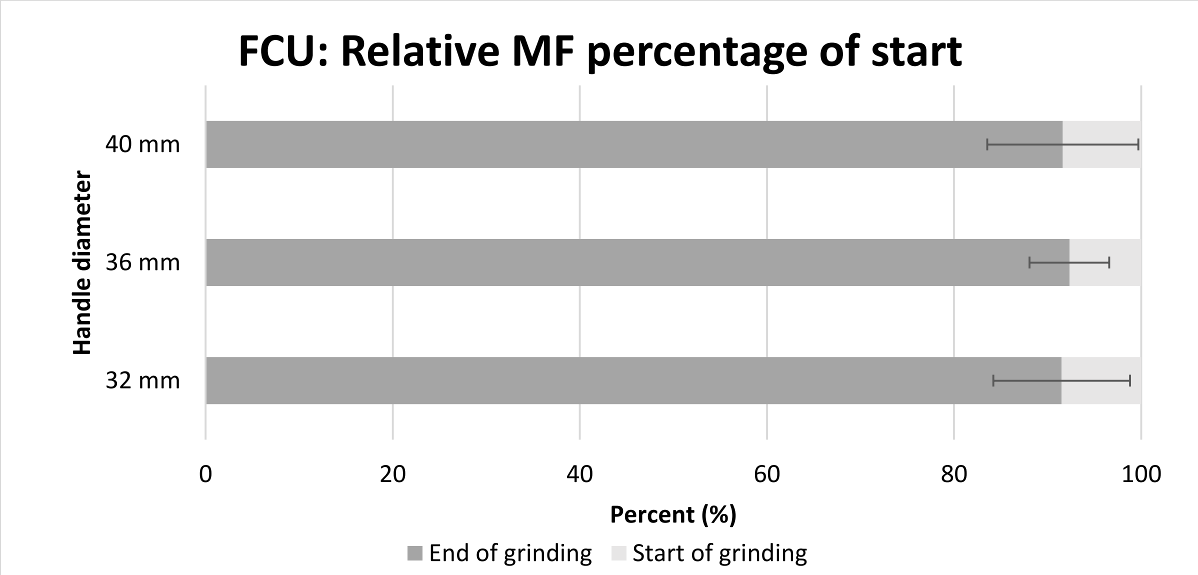

Figure 4 Relative median frequency (MF) as a percentage of start value for flexor carpi ulnaris (FCU)

Discussion

Time to fatigue is longer with the 32mm handles. A statistical significant difference has been found for time to fatigue. Post hoc analyze reveal a difference between 32-36 mm and 32-40 mm. No significant difference has been found between 36-40 mm. Reduction of MVC is significantly different between the 32-40 mm handle. No statistical difference has been found between 32-36 mm and 36-40 mm. The lowest mean drop in MVC is with the 32 mm handle. sEMG show a decrease in MF between the start and the end of grinding, implying that the muscles are fatiguing. No statistical significant difference in MF drop, between the three handles has been found. Results from the present study shows that subjects are able to grind longer with 32 mm handles. Reduction in MVC is lower with 32 mm, even though grinding time is longer. Indicating that a smaller handle diameter result in less fatiguing.

Mastalerz et al. (7) static study stated that the general male population would benefit from a handle of 30 mm. Edgren et al. (5) found greatest grip force by using a 38.1 mm handle and that handles smaller, 25.4 mm or larger than 50.8 mm would result in lower force. Edgren et al. (5) have, unlike the present study, larger variations between handle diameters. A difference of 12.7 mm between 38.1 mm and 25.1 mm make it uncertain if a more optimal handle is in between. Seo and Armstrong (4) developed a formula, based upon hand size and finger length, stating the optimal cylindrical handle diameter for the general population would be around 40 mm. The same size as the largest grinding handle used in the present study and close to Edgren et al. (5) results, 38 mm. These studies cannot be directly compared due to different methodological protocols (e.g. static/dynamic movement). In which static contractions only last a few seconds and grinding being a more enduring movement lasting several minutes. Subjects of the present study might use more muscle fiber activation to keep up the same quantity of work compared to a static MVC test. The longer work duration might explain why the results differ between present study and the static studies.

Shortening or lengthening of the finger flexor muscles resolve in decreased cross-bridges availability (4,15,16). When a specific level of work has to be kept for a particular time a higher number of motor units is recruited (17). So minimizing the amount of motor units recruitment, would help athletes sustain submaximal activity level for longer time (18).

Ratamess et al. (8) have tested bar diameter during different strength exercises and found that 25 mm bar performed best during maximum pulls. Ratamess et al. (8) results are based on dynamic movements like the present study and should therefore be taking into consideration. The other diameters (50- and 76 mm)

Ratamess et al. (8) tested leaved a big gap between variations, compared with the present study. Still, Ratamess et al. (8) results is in range of Mastalerz et al. (7) suggestion of the optimal diameter around 30 mm.

Mentioned studies (4,5,7) suggest different grip sizes as being optimal, at least for static work. It is important to note that hand size influence the optimal handle size. Especially the length of the hand measured from the wrist to the distal end of the middle finger. This is something most studies agree upon (4,5,7). In the present study subjects with a hand length of 17.5 to 21 cm has been recruited, which lead to a more homogenous group.

Time to fatigue is longer with the 32 mm handle; additionally the MVC drop is also statistically lower than 40 mm handle. Since an even smaller handle (e.g. 28, 24 mm) has not been tested it is uncertain if this particular size is the perfect choice. This study only looks at three different sizes. Future studies should look at not only cylindrical handles with the same diameter along its length, but with varying diameters. Kong and Lowe (3) found out that the middle finger produces most force when using a handle with a 30 mm diameter. The rest of the fingers produces most efficiently when the diameter is 25 mm. Supporting this, Neville and Folland (1) suggests that grinders might benefit from custom-made handles. Taking individual finger lengths into account might be the most optimal solution.

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Design of a subject-specific grinding handle: from 3D-scanning to 3D-printing techniques – a technical note

Morten B Simonsen & Anders R Jensen

Abstract

The aim of this study was to develop a method using 3D scanning and printing to make subject-specific grinding handles, to reduce forearm muscle fatigue. Three sets of custom-fitted handles were made and tested against standard fabricated handles for grinding. Maximal voluntary contractions (MVC) were measured before (baseline) and after grinding (post). Additionally median power frequency of surface electromyography (sEMG) was analyzed during grinding. Results indicated less fatigue with the custom fitted handle for flexor digitorum superficial, used for flexion of fingers.

Keyword: Grinding, Custom-fit handle, Subject-specific, 3D scanning, 3D printing

Introduction

Americas' Cup is considered the sailing's Formula One. The history and prestige associated with the America's Cup attracts not only best sailors the world's, but also yacht designers, wealthy investors and sponsors (1,2). It is against the rules to use motors and stored energy over a specific lower limit. Therefore, all power to control sails and daggerboards must be generated by arm cranking, i.e. it is performed by the grinders at grinder pedestal (3).

Grinding is the most physically demanding task onboard the boat, thus resulting in increased risk of injury. This is in fact the highest risk of injury onboard with 3.1 injuries per 1000 hours of sailing since the average across all positions is 2.2 per 1000 hours of sailing. Both elbow and forearm belong to the top five lesion sites for grinders (2). In other upper body dominant sports, forearm injuries usually result from incorrect technique or muscle fatigue (4,5). Neville and Folland (2) mentioned that grinders might benefit from ergonomically optimization of the grinding pedestal, suggesting the use of different handle diameter, custom-fit handle shape and increased grip friction.

Previous findings showed that forearm fatigue was more severe during backward grinding than during forward grinding. (Forearm fatigue during Forward & Backwards grinding - Article 1) An extension of that study suggested that a smaller handle diameter of 32 mm lead to better performance when compared to larger handle diameters. (Handle diameter influence on forearm muscle fatigue during backwards grinding - Article 2) That results from the influence of the length of fingers flexor muscles in griping strength (6–8). The optimal handle diameter has been widely investigated during fingers flexor muscles static contraction (8–11). One thing these studies agree upon is that the subject's hand size plays an essential role in the optimal handle diameter (8,10). Apart from the hand dimensions (length and width), the individual finger length is also important as it affects strength at different grip sizes (9). This supports the idea of that grinders could benefit from custom designed handle shape (2).

Over the last decade, 3D scanning and 3D printing have proven themselves useful in the field of ergonomics in the design of subject-specific equipment. Regarding this project, both techniques can be used towards the development and manufacturing of custom-fit handles for grinders. Hence, the purpose of this study is to design and test a method for making custom-fit handles for grinding using 3D scanning and 3D printing.

Materials and method

Design process of the custom-fit handle

A custom-fit handle was made for each subject for both left and right hand. By the following process:

Handle core

The 3D printed handle core represented in figure 1 and 2A consists of a 120 mm tall cylinder (rod) with a 25 mm diameter. As a reference for the middle finger, an extra cross-sectional cylinder with 32 mm diameter is placed halfway of the previous cylinder rod. Once the cylinder rod doesn't have the same diameter along its axis, it will optimize the total grip strength since each finger can work within its optimal diameter (9). When comparing a cylindrical handle (figure 2B) to the custom-fit one (figure 2C) it is possible to note that the index, ring and little fingers are more aligned with the middle finger (figure 2C). Theoretically, this corresponds to a higher absolute grip strength since each finger works at a proper length (9). Consequently the finger flexor muscles in the index, ring and little fingers are no longer stretched far beyond their optimal working range (6–8).

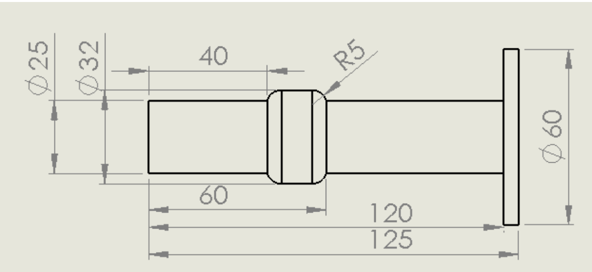

Figure 1: technical drawing of handle core in mm

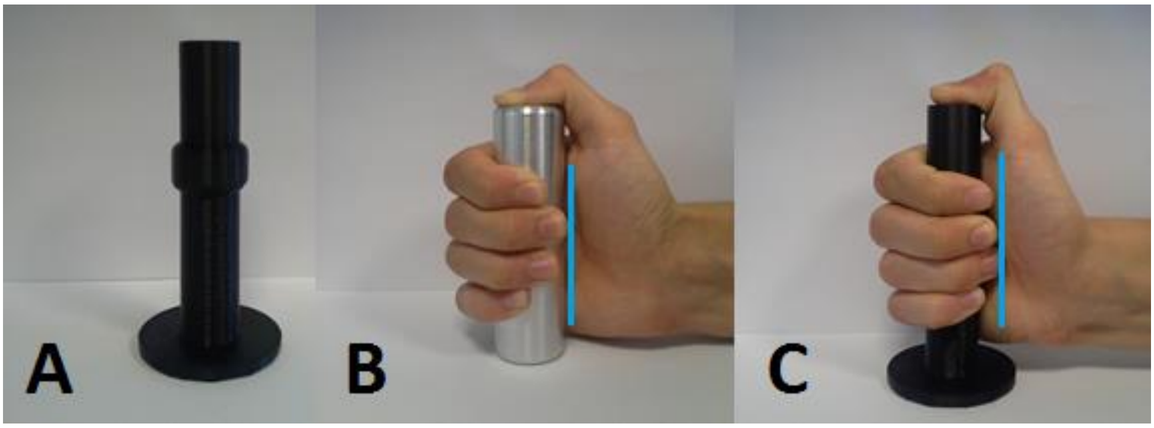

Figure 2: A) 3D printed handle core. B) Griping around the 32mm cylindrical handle. C) Griping around the handle core.

Handprint engraving step

In order to create a custom-fit handle, a thin layer of plasticine (play-doh) was wrapped around the handle core, figure 3A). Subjects were asked to squeeze the play-doh around the handle until they could feel the cylinder core, figure 3B. Once the handle core was released, a final handprint would be engraved in the play-doh, as shown in, figure 3C.

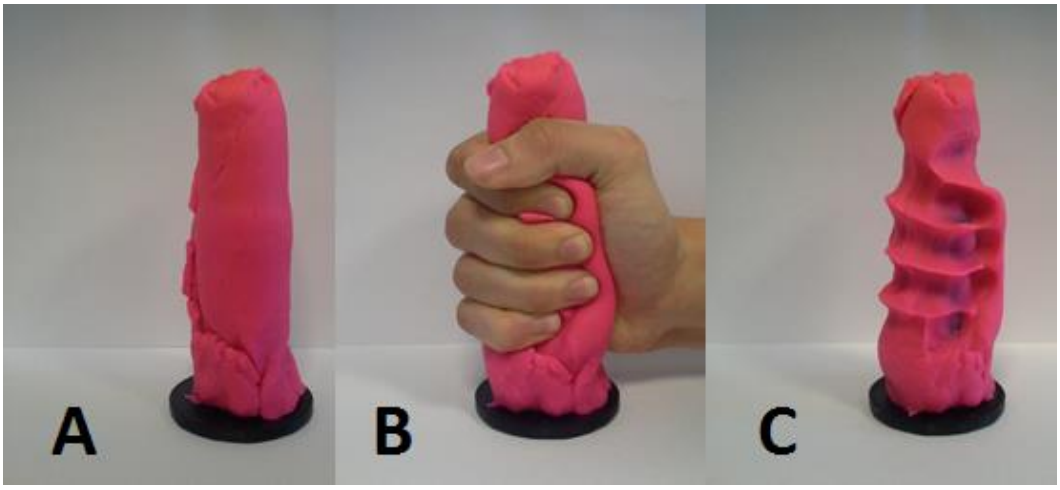

Figure 3 Three steps illustrating the making of the customized handles. A) Play-doh wrapping, B) Gripping around the play-duh, C) Final hand print.

3D-scanning, 3D-modeling and CAD-modeling

The engraved handprint was later 3D-scanned using a MakerBot Digitizer turntable (MakerBot Industries, New York City, USA). A point cloud data file of the respective geometry was acquired and the respective surface mesh was generated by the MakerBot Digitizer's software.

The raw and slightly noisy surface mesh was then imported to Sculptris v.Alpha-6 (Pixologic Inc., California, USA), a digital sculpting software, figure 4A. This software provides a useful manual mouse-controlled "smooth" tool which acts directly on the surface mesh and helps achieving the desired local smoothness. Before finishing the smoothing step it is essential to reduce the surface mesh, using the "reduce" tool, as its resolution tends to increase as the smooth filter is applied (i.e. smoothing increases the number of triangles of the mesh).

The surface mesh was hereafter imported into SolidWorks CAD software v.2013x64 Edition SP05 (Dassault Systèmes SolidWorks Corp., Massachusetts, USA). This CAD software enabled the conversion of surface mesh into a volume mesh and consequently, to a solid geometry. The "Surface Wizard" tool, which can be found in the Scanto3D toolbox, was used for that purpose. Once the mesh was converted to a solid geometry, it was possible to add some features to the part CAD-model, mainly to adjust it dimensions and to perform extruded cuts (creating holes corresponding to the handle core diameter), figure 4B.

3D-printing manufacturing process

The custom-fit handles for different subjects were finally 3D-printed on a MakerBot Replicator 2X (MakerBot Industries, Brooklyn, NY, USA) in ABS plastic, figure 4C. The printer's software MakerBot Desktop v.3.2.2.59 (MakerBot Industries, Brooklyn, NY, USA) was used to generate the printing-files with 0.2 mm of resolution and percentage of infill by 10%.

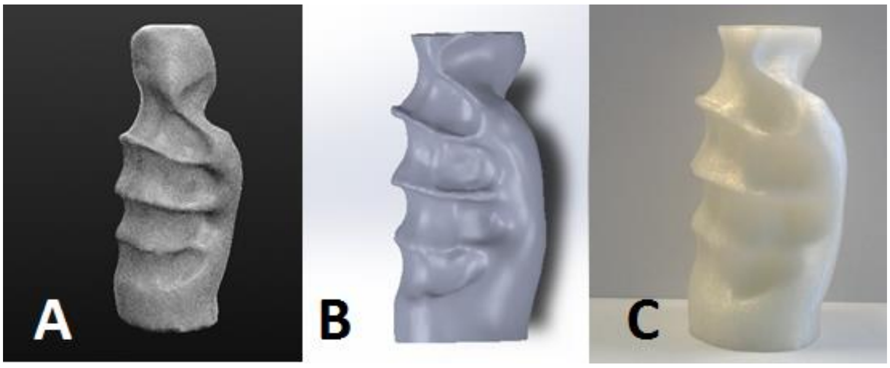

Figure 4 From 3D scan to 3D print. A) A handprint after scan. B) A handprint being processed in SolidWorks. C) The final product after printing.

Experimental method

Demographic

Three healthy male subjects with no history of hand, wrist or arm injuries and limited grinding experience were recruited for this experiment. The mean ± SD age, height, body mass and hand length of these participants were 24.3 ± 0.5 years, 177.1 ± 2.1 cm, 66.6 ± 2.4 kg and 18.4 ± 0.6 cm respectively.

Experimental design

The experiment took place at Aalborg University, Denmark, with a randomized cross over design. The experiment consisted of two tasks: one with a standard handle (SH) made by Harken; the second with the subject-specific custom-fit handle (CH). Each task was performed in two separated days, with 24 to 48 hours between tasks in order to avoid fatigue.

Surface electromyography data collection

Surface electromyography (sEMG) electrodes (Neuroline 720, Ambu, Denmark) in bipolar setup were placed on the skin of the right arm only. The selected muscles of interest were the ones involved in flexion or extension of the wrist as well as in gripping tasks (12). These muscles were the extensor carpi radialis longus (ECR), the flexor carpi ulnaris (FCU) and the flexor digitorum superficialis (FDS), and they were located through palpation techniques such as flexing and extending the wrist or closing and opening the hand. (13) Prior to the placement of the sEMG electrodes, the skin was shaved, cleaned and electrically conductive gel was applied on the skin. The sEMG electrodes were placed on the longitudinal axis of the muscle and the chosen sampling rate was set to 2000 Hz.

Procedures

After the electrodes placement, a five minutes introduction period was taken for familiarization and warm-up on the grinder. Two minutes later, the subject's baseline grip strength was measured with a three seconds maximal voluntary contraction (MVC) test using a hand dynamometer (G200 Model, Biometric Ltd., Newport, UK). The MVC test was repeated three times followed by two minutes break after each trial. Its respective peak value obtained at each test was selected for further analysis. After finishing the MVC test, each subject was asked to grind at a fixed moment of 10 Nm with a cadence of 120 rpm (126W). This second test stopped when each subject was no longer able to maintain that cadence of 120 rpm and the time duration of the test was taken. Time was blinded for subjects. A third post-MVC test was performed immediately after grinding. Please note that the grinder pedestal has a custom build grinding ergometer, a similar setup as reported by Olesen et al.(1).

Signal processing

The sEMG signals were digitally band-pass filtered using a 3rd-order Butterworth filter with a frequency bandwidth of 20-400 Hz. The signals were transformed in MATLAB® (Mathworks, Massachusetts, USA) from the time domain to the frequency domain using a Short-time Fourier Transform with a window length of 10 seconds and 50% overlap. The first and last 5 seconds of sEMG signal were excluded from the analyses to ensure that the data was collected while subjects were grinding with the right cadence. Median frequency(14) (MF) was calculated for the first and last 20 seconds from the remaining signal.

Statistical method

Due to the reduced sample size (N = 3 subjects), only descriptive statics were assessed, mean, standard deviation (SD) and standard error of mean (SE). Relative MVC are calculated as (post/baseline*100) and Relative MF are calculated as (end/start*100).

Results

Time to fatigue and post-MVC (after grinding)

The parameters of time to fatigue and relative decrease of post MVC are presented in table 1.

Table 1 Descriptive data presented in mean, SD and SE for time to fatigue and relative MVC.

Parameter	Handle	Mean	SD	SE
Time to fatigue	SH	165 s	35.7 s	20.60
	CH	168 s	34.9 s	20.13
Relative MVC	SH	86.5 %	3.3 %	1.92
	CH	86.9 %	2.5 %	1.47

Electromyography

The relative drop in MF during the grinding task, table 2.

Table 2 Descriptive sEMG data for each muscle, ECR, FCU and FDS.

Muscle	Handle	Mean (%)	SD (%)	SE
ECR	SH	92.5	3.2	1.82
	CH	90.1	4.9	2.82
FCU	SH	81.4	3.9	2.23
	CH	88.8	7.5	4.31
FDS	SH	73.3	12.3	7.07
	CH	82	11.8	6.79

Discussion

The aim of this study is to develop a method for making custom-fit (CH) handles for grinders. A comparison test between CH and SH shows no big difference between handles, in time to fatigue and MVC, but CH seems to perform slightly better. However, bigger sample size is required to confirm this. This result indicates that the drop in MF is lower with CH, but larger sample and statistical test is required to confirm this.

According to Kong and Lowe (9), the general optimal diameter for the middle finger should be 30 mm and 25 mm for the other three fingers. The handle core used for creating the CH handles is 25 and 32 mm in diameter. The CH handle is therefore a little larger than the recommended by Kong and Lowe (9). It is not possible to make the CH diameter smaller since the inner diameter must be at least 23 mm, otherwise the handle will not to fit the grinding pedestal.

The test subjects states that the CH far is more comfortable then the SH. This comfort aspect indicates that making CH using 3D scanning and 3D printing is of great value. One subject had trouble fitting his index finger in the right-side handle. That shows the importance to give strict instructions while making the hand-print on the play-doh. The assessor needs to be sure that the subject is gripping the handle naturally.

Conclusions and Future Developments

This paper cannot conclude that CH performs better than SH. However, it presents a method for producing custom-fitted handles easy. Further studies are needed to test weather CH can decrease forearm fatigue during grinding. Other sports disciplines, which require hand interaction with equipment, might also benefit from such custom-made handles, like rowing and racket sports.

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Summary

Study one found indications of forearm fatigue being more severe during backwards grinding than forward grinding. These indications are based on statistically significant difference in time to fatigue and MVC. In addition, sEMG shows the same signs but nothing of statistical significance. Preceding with newfound knowledge from study one 'the optimal handle diameter' is established in study two. The optimal handle diameter (32 mm) is based solely on backwards grinding. The 32 mm handle results in less forearm fatigue in relation to time to fatigue and MVC. Finally, study three (technical note) is a description of method to custom-fit individualized handles using 3D scanning and printing. Study one and two as well as related grip strength studies work as the foundation for the developed method in the technical note.

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Forearm fatigue during grinding and development of grinder- specific handle

Master's Thesis

Worksheets

Morten Bilde Simonsen & Anders Rosendal Jensen, 2015Aalborg University10. Semester Sports Technology

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Content

Worksheets guide

The worksheets start chronologically with a description of the America's Cup. Thereafter a description of relevant information about forearm anatomy, neuromuscular- and muscular fatigue, electromyography and collected literature regarding handle design is presented in sections. This theory forms the base of the hypothesis, work questions and chosen methodology. These sections are followed by a comparison of different 3D scan system as well a description of the handle development. Finally the results are presented from study 1-3.

1. America's Cup

America's Cup is a trophy rewarded to the winner of the America's Cup, which is a duel between two yachts, and considered as the sailings formula 1. America's Cup trophy is the oldest international sporting trophy and the first race was back in 1851. The history and prestige associated with the America's Cup attracts not only the world's best sailors, but also yacht designers, wealthy investors and sponsors, and some of the teams have budgets well above 100 million US dollars. America's Cup is not only a competition on sailing skills, but also boat design and fundraising are important factors. One yacht, known as the defender, represents the yacht club processing the America's Cup trophy and the second yacht, the challenger represents the challenging yacht club. The time of each match agreed between the defender and challenger, but in newer times, there has been competition every 3-4 years, and the first to nine wins in the final takes the cup. The defender of the cup decides the rule set, boat type and location. Year 1970 was the first time in history with more than one challenger, which led the defending yacht club, New York yacht club, decided that the challengers had to compete in a variety of races where the winner would be the official challenger. The qualification series has since 1983 been sponsored by Louis Vuitton, and named Louis Vuitton Cup. (Neville et al. 2009; Olesen et al. 2014)

1.1Changes in boat type

In the 2017 edition of the America's cup, was it first decided to race in the boat type AC62. It differs from its predecessor, AC72, by being 7 m shorter and 1.6 ton lighter. However, the decision of using the AC62 boat type for the race in 2017 was overruled on the 1 April 2015 (New Era 2014). Instead, it was decided to use an already developed boat; AC48, which is shorter than the AC62, the reason for the change was to reduce cost, and to make the completion more accessible for new teams (Significant cost saving 2014). Figure 1 illustrates the anatomy of an AC boat type. (Drummond 2013; Gladwell 2014)

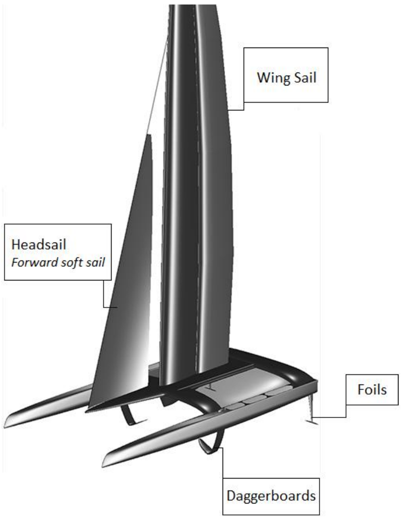

Figure 1 Four characteristic parts of the AC48, Wing- and head sail, foils and daggerboards. Figure modified for project use. ***(Virtac 2014)***

Figure 1 illustrates the AC48 with named main parts, wing sail, headsail, foils and daggerboards. Typical competition speeds for the older version, AC72 class, was above 30 knobs (55 km/h), but in good conditions, the AC72 can reach a top speed above 40 knobs (74 km/h). The fastest recorded speed during the 2013 version of America's Cup was 47.5 knobs (88 km/h), by New Zealand's Team emeralds. The AC48 class is expected to reach similar speed, about 30-34 knobs in tailwind. (Drummond 2013; Gladwell 2014)

1.2 AC72 crew

The crew onboard the AC72 consisted of 11 sailors, which performed different task. The crew onboard the AC48 is diminished to six sailors (Class rule 2015). All America's Cup teams have different lineups depending on the team's strength and weaknesses. Since the AC48 class still have not been in action, the team's lineup remains uncertain. Team Oracles USA crew during the 2013 edition illustrated in figure 2. (Purdy 2013)

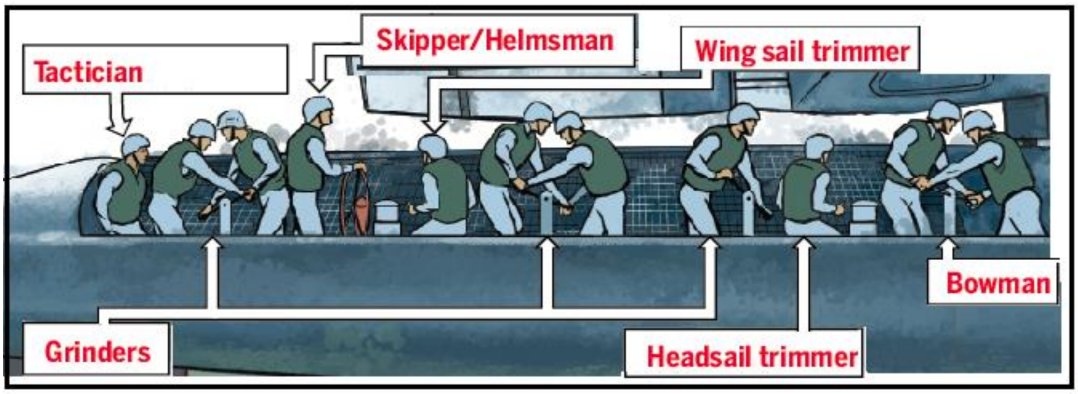

Figure 2 Crew positioning of the team Oracles USA- Figure modified for project use. ***(Purdy 2013)***

In figure 2 positioning of the Team onboard, the Oracles USA is illustrated. The crew consist of a tactician, a skipper, a bowman, sail trimmers, and grinders. The grinders has the most physical demanding task onboard, which is to generate pressure in the hydraulic system. The grinders generate the pressure by hand cycle at the grinder stations. The hydraulic system raises and lowers the daggerboards, figure 3. (Pearson et al. 2009)

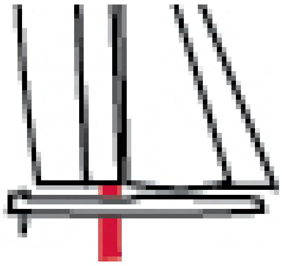

Figure 3 Daggerboad placement. Figure modified for project use. ***(Purdy 2013)***

Figure 3 illustrates the placement of the daggerboards, and is made sure functional by the grinders. (Griffin 2013; O'Donnelley 2013) Since use of stored energy and motors is against the rules, are there almost people grinding non stop. (Olesen et al. 2014)

1.2.1 Functionality of the daggerboards

To foil means that the boat's hull is lifted above the water on the daggerboards, see figure 4, this minimize water resistance dramatically and provides 10-15% more speed immediately. (The Power of Oil 2013)

Figure 4 daggerboards lifting up an AC72. Figure is borrowed from a video at timeframe: 0:41. (Hydrofoils 2013)

As seen in figure 4 the hull is no longer in the water due to the function of the daggerboards. Another feature of the daggerboards is to stabilize the boat so It does not capsizing under strong crosswinds. The hydraulic system is the heart of this boat type, without the system would the boat not be capable of reaching the speed that it does. As mentioned earlier it is forbidden to use motors onboard or stored energy, which means all energy has to be produced to order. Grinders is therefore required to grind to increase or keep the pressure in the hydraulic system. During foiling, the position of the daggerboards will constantly be adjusted to keep the boat in balance, failure to do so can have catastrophic consequences. The pressure in the hydraulic system are used to raise, lower and control the position of the daggerboards. Especially during cornering are the hydraulic system required to work perfectly, because the pressure on the daggerboards are more than doubled compared to straight sailing, see figure 5. (The Power of Oil 2013)

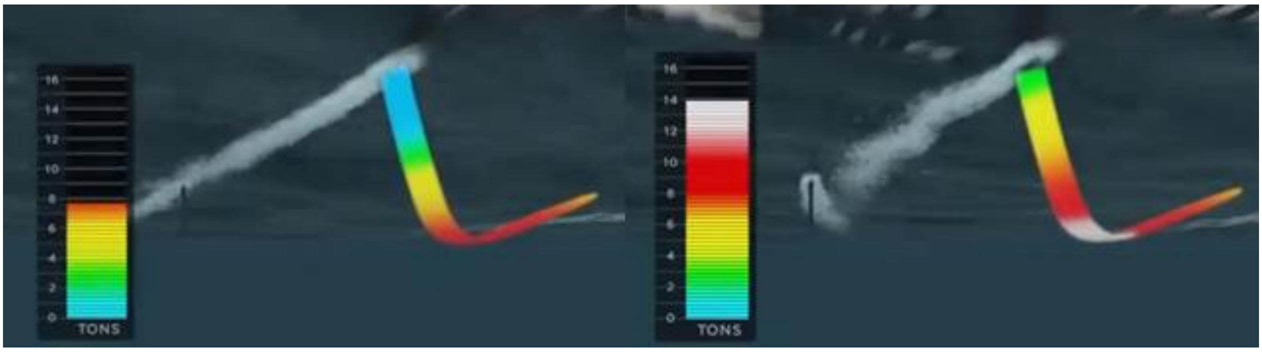

Figure 5 Pressure scales indicating where the pressure is biggest on the daggerboards. Figure 5 is borrowed from a video at timeframe: 1:28 and 1:22. Left is during straight sailing and right is during cornering (Hydrofoils 2013)

The color index seen in figure 5 illustrates how much pressure is applied to the daggerboards when sailing strait (left picture) and how it increases then turning around a corner (right picture).

2. Muscle functionality

The skeletal muscles have many characteristics; in the next section are some of these factors described in, alongside with a brief description of the structure of skeletal muscles. One of the functions of the skeletal muscles is to produce skeletal movement. Contraction from the muscles pull on tendons and thereby move the skeleton. Tension in the skeletal muscles makes it possible to maintain body posture and without constant muscles activity, would it not be possible to sit upright, stand or holding on to something. Muscles are organized in bundles, which contain bundles of smaller scale, and so on down to single muscle fibers, also termed muscle cell, see figure 6. (Martini & Nath 2009)

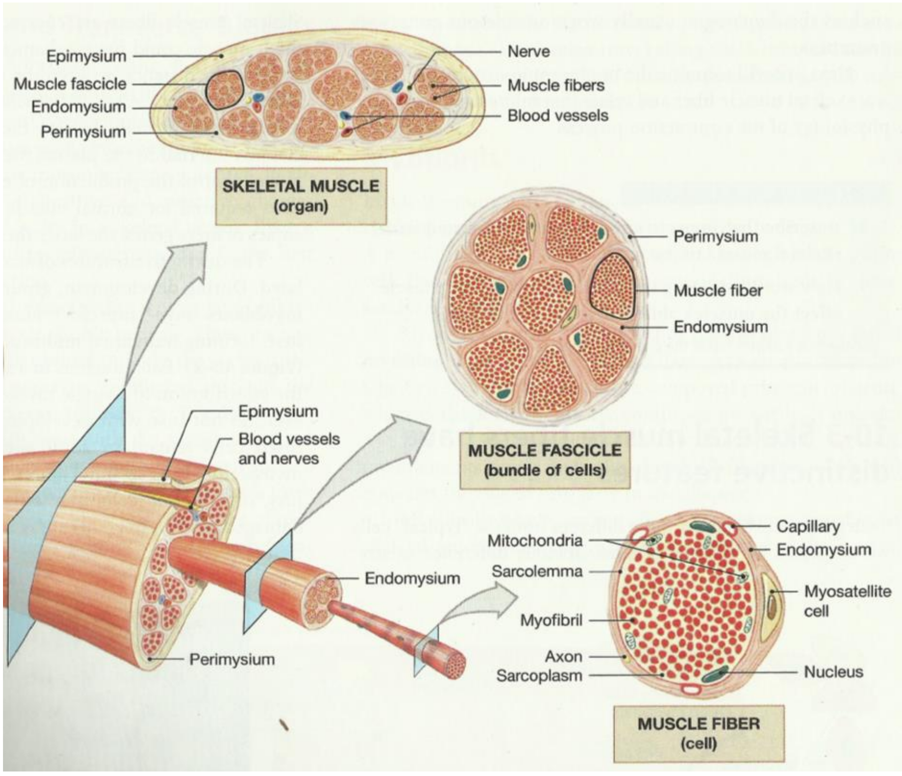

Figure 6 Skeletal muscles organization (Martini & Nath 2009, pp. 295)

As seen in figure 6 the a skeletal muscle contains countless muscle fibers arranged in bundles and the length of a muscle fiber can reach up to 30 cm, depending on the muscle, while they are only 10–100 my wide. Neural signals initiates muscle contraction. Neurons that only serve this purpose are termed motor neurons. One single motor neuron can innervate 200 to 2000 muscle cells depending whether fine or coarse activation is required. The motor neurons also innervate the same muscle cell several times. The connection between a motor neuron and a muscle cell is termed neuromuscular junction. (Martini & Nath 2009)

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2.1 Neuromuscular- and muscular fatigue

One definition of fatigue is "then a muscle no longer can produce the required amount of force to uphold a certain level of activity". There exist two kinds of fatigue: Neuromuscular fatigue and muscular fatigue. In short, neuromuscular fatigue is then nerves lacks the ability to create strong enough signal to the muscles. Muscular fatigue happens when the muscle fibers no longer are able to contract - called metabolic fatigue. (Martini & Nath 2009)

A definition of neuromuscular fatigue is "a decline in muscle tension with repeated stimulation over time". A number of complex factors causes motor unit fatigue. Voluntarily muscle contraction is occurring in a nervous system hierarchy: (McArdle, Katch & Katch 2009)

1. Central nervous system
2. Peripheral nervous system
3. Neuromuscular junction
4. Muscle fiber (McArdle, Katch & Katch 2009)

Fatigue happens when a passage from one' step to another is interfered with. An interruption between point 3 and 4 could result in fatigue in the neuromuscular junction, meaning a motor unit fails to deliver an action potential to the fiber. (McArdle, Katch & Katch 2009) Muscular fatigue or metabolic fatigue happens due to several factors:

- Decline in metabolic reserves inside the fibers of the muscle
- Damaged sarcolemma and/or sarcoplasmic reticulum
- Decease in calcium ion binding to troponin and enzyme altering.
- Lower pH value in the whole muscle (Martini & Nath 2009)

The fact that a muscle is fatiguing is an increasing effect what will get worse and thereby require higher neural activity to recruit more muscle fibers. This increasing effect will result in performance reduction for the entire musculoskeletal system. If an athlete is involved in a moderated activity where ATP demands can be met through aerobic metabolism, the athlete will not experience fatigue before the glycogen, lipid and amino acid reserves are depleted. If there, however, will be a sudden burst in activity level, most ATP is provided by the glycolysis. Glycolysis only last for a couple of seconds to a few minutes while lactic acid is building up and lowering the pH in the muscle tissue leading to muscle dysfunction.

(Martini & Nath 2009) So for the muscle to not fatigue quickly, a few pointers has to be taken into account

- Substantial energy reserves within the muscles
- Normal circulatory supply
- Normal oxygen levels supplied through bloodstream
- Normal blood pH values (Martini & Nath 2009)

Interfering with any of the four pointers listed above will make the athlete experience muscle fatigue prematurely. (Martini & Nath 2009)

2.2 Forearm anatomy

In the next section will the functions of superficials muscles in the forearm be explained. Deep muscles is not mentioned since they are not investigated in the present study despite the fact that they also move the wrist and fingers. For illustration of the forearms anatomy, see figure 7 and 8.

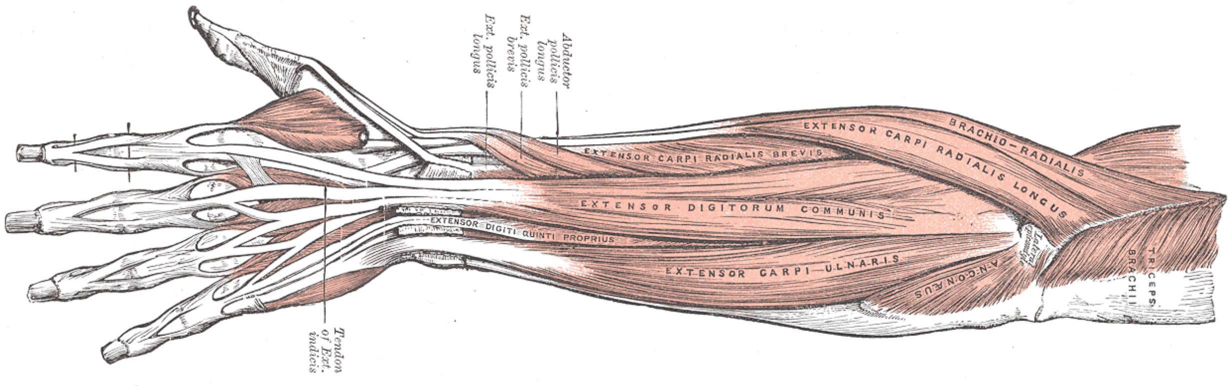

Figure 7 Posterior side of the forearm ***(Grip training 2015)***

Figure 7 shows superficial muscles on posterior side of the forearm, including extensor carpi radialis brevis, extensor carpi ulnaris etc., table 1 present additional information. (Martini & Nath 2009)

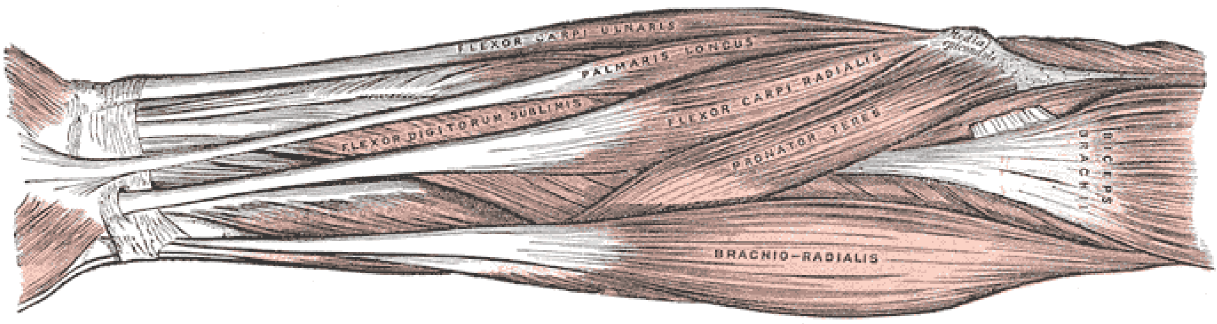

Figure 8 Anterior side of the forearm. ***(Grip training 2015)***

Figure 8 shows superficial muscles on posterior side of the forearm, including flexor carpi radialis, flexor carpi ulnaris palmaris longus etc., table 1 present the action of each superficial muscle. (Martini & Nath 2009)

Table 1 Superficial muscle overview, action and additional notes. Table modified for project use. (Martini & Nath 2009, pp. 367)

Posterior side	**Action**
Extensor carpi radialis longus	Extension and abduction at the wrist
Extensor carpi radialis brevis	
Extensor carpi ulnaris	
Anterior side	**Action**
Flexor carpi radialis	Flex and abduct at the wrist
Flexor carpi ulnaris	
Palmaris longus	Flexion at wrist
Pronator teres	Hand pronation and flexion of the wrist
Bachio radialis	Flexion of the forearm
Flexor digitorum superficialis	Flexion of the fingers

As seen in the table 1 all of the muscles mentioned takes part in flexing or extending the hand. Muscle activity will be measured on Extensor carpi radialis longus, Flexor carpi ulnaris and Flexor digitorum superficialis (figure 7 and 8) since all three muscles are involved in finger flexion, flexion or extension and stabilizing the wrist.

3. Electromyography

Electromyography (EMG) is a technique tomeasure electrical signals from muscles motor units, during muscle contraction. EMG has proven useful in many different areas, for example: To diagnose abnormalities in the nervous system, control electronic prostheses, but EMG is also commonly used to investigate muscle fatigue (Chowdhury et al. 2013; González-Izal et al. 2012). There exist two different methods for measuring EMG, surface electromyography (sEMG) and intramuscular electromyography (iEMG). sEMG is a non-invasive method to measure muscle activity using electrodes on superficial muscles. iEMG is an invasive method which also can measure deep muscles. iEMG measurements is not measured in the present study and therefore will not be described further. (Chowdhury et al. 2013)

3.1 Signal processing

Figure 9 shows a raw sEMG measurement during three contractions. Figure 9 illustrate how difficult it is to interpret anything from a raw signal, and therefore is various types of signal processing techniques used to remove noise.

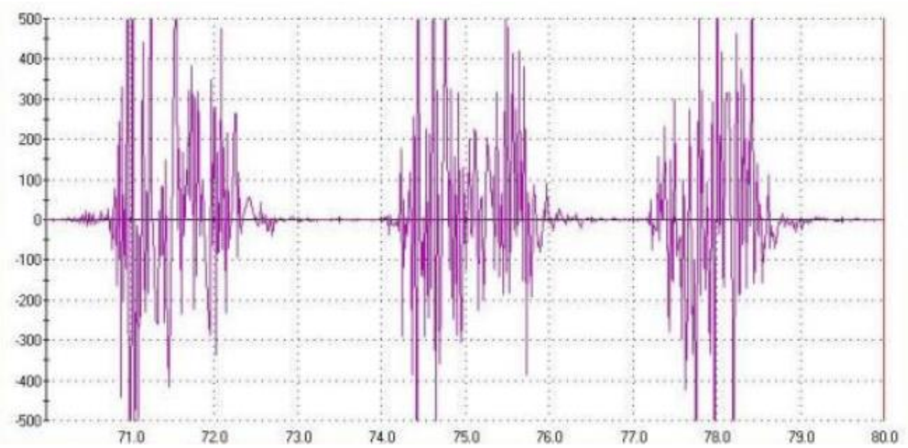

Figure 9 Raw EMG signal. X-axel: Time, y-axel: amplitude in micro-volt. ***(Florimond 2010 pp. 18)****.*

Raw EMG offers valuable information in a useless form. During EMG recordings, is various types of noise contaminate it. Analyzing and classifying EMG signals can be complicated. The next sections gives a review of different types of noise and various methods for analyzing muscle fatigue from EMG recordings. (Chowdhury et al. 2013)

3.1.1Noise in general

Raw EMG contains various noise signals or/and artifacts. The attributes of the EMG signal can depend on internal structures within the subject, for example, skin temperature, skin formation, measuring site and tissue structure. These factors produce different types of noise within the signals, effecting the measurement. There exist different methods to eliminate noise within the EMG signal by using various filters. The main challenges in analyzing EMG signals are; Inherent noise in electrode, movement artifact, cross talk and internal noise. (Chowdhury et al. 2013)

3.1.2 Filter

As earlier mentioned is it not possible to extract information direct from a raw EMG signal; it can be masked by other signals or buried in nose. Therefore is further processing required to enhance the relevant information. (Bronzino 2006)

3.1.2.1Butterworth

The butterworth filter is a digital filter designed for signal processing and is designed to have as flat frequency response as possible in the passband. (Butterworth 1930) A passband or bandpass filter describes a range of frequency in which the signal can pass through. (Shenoi 2006) A butterworth filter can be modified so that it contains low-, high- and band-pass function. In this project the butterworth filter has been constructed with a n=3 order and a normalized cuff off frequency of 400/1000 Hz for low pass filter and 20/1000 Hz for high pass filter. The order n' is in what angle the frequency should be cuff off. sEMG frequency is normally between 20-400 Hz, and therefore is this often used as band pass filter in sEMG studies. (Butterworth 1930)

3.2 Muscle fatigue analyze

The first type of contraction that where studied using sEMG techniques was either static or isometric contractions. The reason that sEMG signal, recorded during isometric contractions is simpler to analyze is that the mean value of the sEMG signal do not depend on time. Because of this, some frequency-based techniques, Fourier transforms or fast Fourier transforms can be used to detect changes in the power spectral content in the EMG signal. However, sEMG measurements during dynamic are more relevant for daily function. However, other factors influence sEMG signals during dynamic contractions compared to isometric contraction. Under dynamic contraction, is joint angles changing, which will cause change in muscle fibers with respect to recording electrode. In addition, are there other factors influence sEMG signals during dynamic movement. Rapid change in motor units recruitment and de-recruitment and changes of muscle force during movement. This rapid change will cause faster changes in signal properties compared to static contraction, in turn resulting in non-stationary. Therefore is the traditionally frequency techniques not appropriate, for processing dynamic sEMG signal, and more complex techniques are necessary. Therefore new techniques were developed. The techniques developed were, time-frequency techniques, which allow study the sEMG signals. Time-frequency techniques monitors changes in the EMG signal, due to muscle fatigue. In the next sections, some of the EMG parameters obtained from different techniques will briefly be described. (González-Izal et al. 2012)

3.2.1 Time domain

Time domain is the analysis of mathematical functions or physical signals with respect to time. In the time domain is the signal is the values known for all real numbers. (Bronzino 2006)

3.2.2 Frequency domain

Frequency domain is the analysis of mathematical functions or signals with respect to frequency, instead of time as in the time domain. Any signal can be described as a continuum of sine waves with different amplitudes and phases. Means, amplitudes and phases of the sine waves describe the frequency representation. Before a signal can be presented in the frequency domain must it be rectified, since it is not possible to calculate sinus on negative numbers. (Bronzino 2006)

3.2.3 Short-time Fourier transform

Short-time Fourier transform (STFT) is a method were non-stationary can be analyzed. The signal is dividing into short segments. The length of the segments are chosen such that each one by itself can be considered a windowed sample of a stationary process. The duration of the segments is determined from the signals characteristics. The segmented signal are represented in the frequency domain, STFT is defined as: (Bronzino 2006)

$$STFT_s(\omega,\tau) = F\{s(t)w(t-\tau) = \int_{-\infty}^{\infty} s(t)w(t-\tau)e^{-j\omega t}dt$$

w(t) is the window function, x(t) is the signal to be transformed. (Bronzino 2006)

3.2.4 SEMG amplitude based parameters

There is two parameters that are used to quantify amplitude and magnitude of an EMG signal: root mean squared value (RMS) and averaged rectified value (ARV). (González-Izal et al. 2012)

$$ARV = \frac{1}{n}\sum_{n}|x_n|$$

$$RMS = \sqrt{\frac{1}{n}\sum_{n} x_n^2}$$

n is the total number of samples and x_n is the value of the EMG signal. Despite ARV and RMS is calculated in different ways, the results from each is quite similar. There are different factors that influences the amplitude of the EMG signal, such as the number of active motor units, discharge rate. The signals amplitude has been reported to increase during submaximal isometric contraction and decrease during maximal. Moreover, the tendency is similar during dynamic contraction. However, Dideriksen et al. (2010) shows that the relationship between sEMG amplitude and force differed between different protocols. (González-Izal et al. 2012)

3.2.5 Spectral analysis

Mean and median frequency are traditionally used to detect changes in the spectral content of an EMG signal, by using Fourier transform. The next two equations explain how mean and median frequency is obtain: (González-Izal et al. 2012)

$$Fmean = \frac{\int_{f1}^{f2} f \cdot PS(f) \cdot df}{\int_{f1}^{f2} PS(f) \cdot df}$$

$$\int_{f1}^{Fmedian} PS(f) \cdot df = \int_{Fmedian}^{f2} PS(f) \cdot df$$

$PS(f)$ is the EMG power sprectrum that is obtained by the calculated Fourier transform. $f1$ and $f2$ is values of the bandwidth filter of the electrode ($f1$ = lowest and $f2$ = highest frequency). These two parameters, median and mean frequency, relate to changes in muscle fibers conductions velocities and in changes of the motor units action potential waveform. Mean frequency usually decreases during static contractions. The same tendency is reported during dynamic fatiguing task. However, no difference has been found in some types exercises, like walking for instance. Petrofsky and Lind (1980) findings might be able to explain these phenomena. They found that the intramuscular temperature could increase spectral content of the EMG signal, and thereby increase the mean frequency. This will result in two opposing effects during a fatiguing activity: a decrease in the mean frequency because of muscle fatigue and an increase in intramuscular temperature due to the activity. Moreover, it is possible what these two factors can compensate each other and thereby balance each other out. (González-Izal et al. 2012) Decreasement in mean and median frequency is a sign of fatigue. Since fast-twitch muscles fires at higher frequencies than slow-twitch muscles.

4. The right grip

The following section will present results, discussions and conclusions from the literature. Earlier studies have shown that grip strength are affected by handle size, during static as well as some specific dynamic work.

4.1 Diameter and force output

Edgren et al. (2004) found that maximum force is differs between different handle diameter. Subjects hand size was measured, since the length and width of the hand can have an impact. Subjects maximal grip force was measured on five different sized hand dynamometers, for 5 seconds each. The diameters of the dynamometers were 25.4-, 38.1-, 50.8-, 63.5- and 76.2 mm. See figure 10 for maximum force generated.

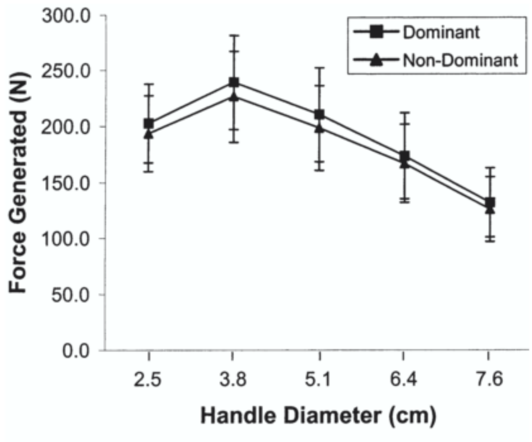

Figure 10 Average force generated with different handles sizes. (Edgren et al. (2004), pp. 248)

Highest force production, happened with the 38.1 mm sized handle, figure 10. Smaller and larger than 38.1 mm diameter would decrease the force output (Figure 10). Results indicate that general optimal handle diameter would be around 38.1 mm, regardless of hand size. However, 11% of the subjects generated highest force when using the 50.8 mm diameter handle. The 11% suggest that hand size is important and individual customization can improve force output in gripping work.

4.2 Grip in dynamic exercises

Edgren et al. (2004) study was based on static/isometric contractions, however most exercises and in the America's Cup the movements are dynamic. It is therefore important to look at grip strength in dynamic settings. Some of the sailor's assignment in the America's Cup is to generate pressure in the hydraulic system by grinding (Pearson et al. 2009).

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According to Pearson et al. (2009) can forward grinding be associated with bench pressing and backwards grinding to bench pull.

Ratamess et al. (2007) investigated the effect of handle diameter during different dynamic push- and pulling exercises. The purpose of their study was to examine how the diameter of a weightlifting bar influenced strength exercises, table 2.

Table 2 Listing of pushing and pulling exercising with three different bar diameters (Ratamess et al. 2007)

Pushing exercises	**Pulling exercises**
Bench press	Deadlift
Seated shoulder press	Bent-over row
	Upright row
	Arm curl

Ratamess et al. (2007) tested three different bar sizes: 25.4-, 50.8- and 76.2 mm in diameter. The results showed that incensement in diameter would result in a lower 1-repetition maximum for the pulling exercises only, table 2. The pressing exercises was unaffected. Ratamess et al. (2007) results indicate that only in exercises where grip strength is an important factor the diameter of the bar matters. However, even if a larger diameter has no effect on the strength performance there is still the aspect of discomfort. Some subjects experienced greater discomfort then using the 50.8- and 76.2 mm bar during pressing exercises.

Ratamess et al. (2007) did not measure electromyography, but subjects reported a higher level of delayed onset muscle soreness in the forearm after using the 76.2 mm bar. Higher levels of muscle soreness could indicate that larger diameter improves stimulus to forearm muscles

When projecting Ratamess et al. (2007) findings to forward grinding, the size of the grinding handle might not influence performance. However, forward- and backwards grinding will be performed by the same grinder and since backwards grinding is similar to a pulling exercise (Pearson et al. 2009), handle diameter when grinding might have an impact on muscle stimuli in the forearm. (Ratamess et al. 2007)

Ratamess et al. (2007) mention that some athletes with big hands might give different results since they measured the length and the width of their subject's hands and found that there was a negative correlation between hand length and the increase of the bar diameter.

Again, looking at grip strength using a bar or handle, the hand size influence the results in static (Edgren et al. 2004) as well as in dynamic exercises.

Ratamess et al. (2007) measured maximum strength during one repletion maximum, but also the influence of muscular endurance. Subjects was hold each bar in an upright position with arms straight down the sides for as longs as possible. The weight on the bar was equal to the subjects 75 % of predetermined 1RM in deadlift. Regarding maximum strength, the smallest diameter, 25.4 mm, performed best, the same goes for the endurance test. In addition, the difference between 50.8 mm and 76.2 mm bar in endurance test was non-significant. The endurance test was static.

4.3 Hand size and manual effort

Grant et al. (1992) tested three different handle sizes depending on subjects hand dimensions. The first handle size was equal to the diameter inside the hand, the second handle was 10 mm smaller in diameter. Third size was 10 mm larger in diameter contra the first. Grant et al. (1992) investigated not only static grip strength but also manual effort (e.g. the handle diameters effect on manually pulling an object). Just like the maximal grip strength wary then changing the handle size so does the manual effort. Grant et al. (1992) get best results using the handle being 10 mm smaller than the inside grip. These findings suggest that it might not be possible to make a "one size fit all" handle since it depends on the subjects hand size and finger length. Grant et al. (1992) tested only three different handle sizes and only varying the diameter by ±10 mm. It is unclear whether the 'optimal' handle diameter is supposed to be even smaller or bigger than the inside grip.

4.4 Optimal handle size by formula

Seo and Armstrong (2004) concluded in there study that the optimal handle diameter for highest force output, is around 38 mm. They came up with an equation based on a subjects hand dimensions. Thereby being able to estimate the most effective/optimal handle diameter for that individual. The optimal diameter is then the tip of the middle finger and the tip of the thumb are aligned parallel along the longitudinal axis of the handle, figure 11a.

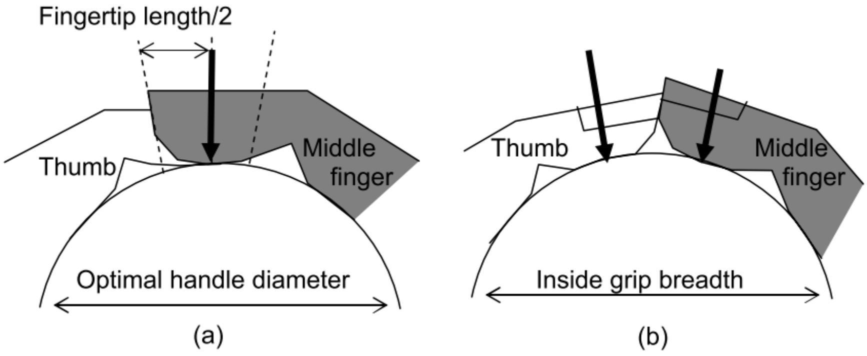

Figure 11 Definitions of optimal handle diameter (a) and inside grip breadth (b). (Seo and Armstrong 2004, pp. 742)

As seen in figure 11a the thumb and middle finger barely come across each other being the optimal setting for highest grip force. With the 'optimal handle diameter formula' Seo and Armstrong (2004) comes up with a mean diameter of 40 mm, which is only 2 mm away from Edgren et al. (2004) study. However, in Seo and Armstrong's (2004) study is the diameter of the cylindrical handles the same along length of the handle, meaning that this equation does not take into account that this 'optimal' diameter may not be the best for the remaining fingers.

The formula is based on the length of the middle finger, figure 11b, which normally is the longest finger, and thereby not taking into account whether the other, shorter fingers is contributing, maximally to the force generated. Seo and Armstrong (2004) point out, then handle diameter increases, fingers will open more causing the moment arm for the finger flexor muscles to decrease, and reducing the grip force. Since "the optimal handle size" is based on the longest finger, the three other fingers will properly experience that the finger flexor muscles will decrease.

Therefore, Seo and Armstrong's (2004) formula is a good estimation for a cylindrical handle but the handle has to vary in size on the longitudinal axel to get maximum force from each finger. A study by Kong and Lowe (2005) was able to detect the optimal handles size/ maximum force development for each finger. According to Kong and Lowe (2005), the middle finger produce the greatest force at a 30 mm handle and for the other fingers 25 mm was the most optimal.

5. Method

The following text outlines the aims and purpose of the current study. Three studies are introduced as well as a brief methodological description of each. The intension of this chapter is to give an overview of this body of work. Additionally there will be a general presentation of the test protocol and equipment used.

5.1 Motivation

America's Cup is the pinnacle of sailboat racing (Neville et al. 2009; Olesen et al. 2014). With the fast changing rule set, is it necessary for both boat designers as well as athletes to be able to overcome the challenges to get an edge over the competitors (New Era 2014). The most physically demanding task onboard is grinding (performed by Grinders), where arm cranking is performed to produce pressure in the hydraulic system used for controlling the sails, and daggerboards. Grinders have among the highest numbers of injuries onboard with 3.1 injuries per 1000 hours of sailing, 8-13% and 8-11% of these injuries are related to elbow and forearm injuries during sailing, respectively (Neville et al. 2009). In other upper body sports like rowing, it has been reported that rowers also have problems with forearm injuries due to improper technique or muscle fatigue (Rumball et al. 2005). Neville and Follan 2009 suggest that grinders might benefit from ergonomically optimizing the grinding pedestal, and suggests different handle diameter, custom handle shape and increased grip friction.

The previous chapters has provided a summary of America's Cup, forearm anatomy and the current research of handle design. Moreover, it is it clear what there are is a gab in the literature regarding muscle fatigue in the Americas Cup, as well as general analyses of handle design during dynamic motion. Ratamess et al. (2007) showed that bar diameter has influence on 1RM max during dynamic pull exercises, however this is shot time movement, so it stills remains unclear if this tendency continues during longer enduring tasks. Other studies (Grant et al. 1992; Edgren et al. 2004; Kong & Lowe 2005) have investigated grip strength during static contraction, and results showed what handle design have influence on grip strength. Nevertheless, as mentioned earlier the effect of handle design have not been investigated during longer dynamic tasks. This research aims to fill a small number of the many knowledge gaps within the literature by quantifying muscle fatigue with sEMG and maximum voluntary contraction (MVC) test under grinding with different types of handles and direction. However, further research will be required before recommendations for handle design for other sports task, such as cross-country skiing pole.

5.2 Aims

The purpose of this project is to develop a concept, to produce custom-fit handle for Americas Cup grinders. But before this can be accomplished, is it necessary to develop a test procedure what can detect changes is muscle fatigue and understand which factors contributes to this muscle fatigue, and how it can be reduced. Data are to be collected from subjects using a grinder ergometer, which is developed to mimic a grinder station, while sEMG and MVC power reduction are recorded. There is no data of this kind within the current literature. The data collected will provide valuable information for handle design, and test procedure for evaluating forearm fatigue during grinding. The contributions of each study to the overall topic are presented in detail, in the next sections.

There are four major aims for this study, se figure 12 for illustration:

1. Compare forwards and backwards influence on muscle fatigue.
2. Investigate optimal handle diameter
3. Develop a method for making custom fit handles.
4. Compare custom-fit handle with a standard handle.

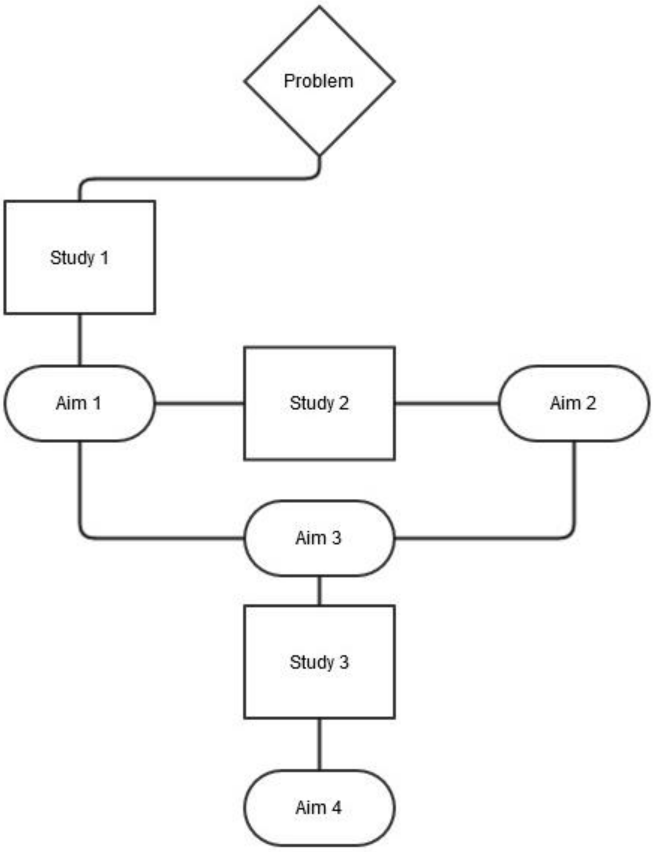

Figure 12 Flow diagram for project aims

5.3 Methodological overview

5.3.1Study one - Forearm fatigue during forward and backwards grinding

In this study two different interventions will be investigated:

- Forward grinding
- Backwards grinding

Pearson et al. (2009) suggest that backwards grinding is related to pulling exercises in strength training. Ratamess et al (2007) showed that grip strength is more important in pulling exercises. Hypothesis: Backwards grinding is more fatiguing for forearm muscles than forwards grinding.

5.3.2 Study two - Handle diameter influence on forearm muscle fatigue during backwards grinding

In this study three different diameters will be tested, to find the optimal diameter during backwards grinding for the individual subject:

- 32mm
- 36mm
- 40mm

Edgren et al (2014) showed strength was highest with handles diameters. Grent et al. (1992) showed that smaller handles resulted in higher MVC in static studies. Hypothesis: Smaller diameter results in less forearm fatigue.

5.3.3 Study three - Design of a subject-specific grinding handle: from 3D-scanning to 3D-printing techniques – a technical note

In this study three customized handle sets will be produced, one for each subject will be compared with the standard handle during backwards grinding.

- Standard handle
- Custom fit handle

The purpose of this study is to develop a method for making custom-fit handles. Therefore are no hypothesis formulated.

5.4.1 Study design

All three studies are performed with a randomized crossover design. It is not uncommon in physical or health related studies to use this design, since the subjects cannot be compared with one another, due to individual factors that affect the results. The same applies to this study where unexperienced individuals have to grind to the point of muscular fatigue. (Machin & Campbell 2005)

5.4.2 Inclusion/exclusion

Only healthy male subjects, with no history of hand, wrist or arm problems participated in the studies study 1-3. In addition, the subjects hand length has to be within 17-21 cm for more homogenized grouping.

5.5 Equipment list

- sEMG Amplifier: 16 channels surface EMG acquisition system, S/N: 0544205 (LISin Bioengineering Center, Torino, Italy)
  - sEMG cable 16 channels and cable for reference and reference strap.
- Rack-Mount Connector Accessory for E/M Series DAQ Devices: NI BNC-2090A, (National Instruments, Austin TX, USA)
  - Cable to connect it to amplifier: 184749B-01 1 Meter, 37000843 (National Instruments, Austin TX, USA).
- USB-6121 BNC, 16-bit, 400kS/s M Series DAQ, Integrated BNC, Bus-Powered, S/N: 18252A8 (National Instruments, Austin TX, USA)
- Single patient-surface electrodes (Neuroline 720, REF 72001-K/12, Ambu A/s, Malaysia)
- Hand dynamometer: G200 Model S/N: 10945 (Biometric Ltd., Newport, UK)
- Power supply for dynamometer (390 Sensor Supply Noraxon, Inc., S/N: 39009016, Velamed Medzintecnik GmbH, USA)
- Custom made grinder (Olesen et al. 2014)
- Torque transducer (Olesen et al. 2014)
- Gel/paste for sEMG preparation: Everi (Spes medica, Italy)
- Hollow cylindrical handle with varying diameter see Chapter 6 for work drawings.
- Hollow cylindrical handles - diameter, 32, 36, 40 mm. Hole diameter: 22,2 mm
- Play-Doh (Hasbro Inc., Pawtucket, Rhode Island)
- MakerBot Digitizer turntable (MakerBot Industries, New York City, USA)
- MakerBot Replicator 2X (MakerBot Industries, Brooklyn, NY, USA)

Software:

- Mr. Kick III preview (KnL incl. Wirex support, Aalborg University, Denmark)
- *Driver:* Measurement & Automation Explorer (National Instruments, Austin TX, USA)
- MATLAB® vR2015a (Mathworks Inc., Massachusetts, USA)
- SPSS Statistics v.22, (IBM Corporation, Armonk, New York, U.S.)
- LabView v.2013x32 Edition, (National Instruments, Austin TX, USA)
- Sculptris v.Alpha-6 (Pixologic Inc., California, USA)
- SolidWorks CAD software v.2013x64 Edition SP05 (Dassault Systèmes SolidWorks Corp., Massachusetts, USA)
- MakerBot Desktop v.3.2.2.59 (MakerBot Industries, Brooklyn, NY, USA)
- MakerWare for digitizer V 3.6.0.78 (MakerBot Industries, New York City, USA)

5.6 Dynamometer and maximum voluntary contraction

Measuring grip strength before and after grinding, a maximum voluntary contraction (MVC), was done with a hand dynamometer (G200 Model, Biometric Ltd., Newport, UK), figure 13. (Biometrics Ltd 2015)

Figure 13 Hand Dynamometer G200 ***(Biometrics Ltd G200 2015).***

As seen in figure 13 the G200 can vary in grip size, from one to five (Biometrics Ltd G200 2015). Grip size three was chosen as it was the average installation and all subjects should be able to grip around it. The output is monitored in Mr.Kick III preview (KnL incl. Wirex support, Aalborg University, Denmark), and the output is given I volt. The output in volt can be converted to newton, using the sensitivity information, 5.65 mV/N, this was performed before further analysis.

5.7 Preparation and electrode set-up

Prior to the tests the skin was prepared before placing the sEMG electrodes to achieve the best signal. Preparation includes removing hair and cleaning the skin area by applying a specialized gel. The gel contains small grains that remove dead skin cells. In addition, most gels contains alcohol and a formula that increases the skins electrically conductivity. (Florimond 2010)

After preparation, sEMG electrodes are carefully placed on the belly of the muscle. Placing the electrode to close to a tendon will cause less of a signal since there in this position will be fewer and smaller muscle fibers. In addition, the electrodes should not be placed too far to the edge of the muscle; it might course cross talk. The electrodes should be placed on the longitudinal axial of the muscle parallel to the muscle fibers so the action potential runs through the electrode. (De Luca 2002)

There are different ways to do the electrode setup. Well-known setups include monopolar- and bipolar setups. Monopolar setups consist of one electrode on the active muscle and a reference point. However a monopolar setup is said to be unusable doing dynamic movements (Robertson et al. 2004). Subjects in this project will be grinding, therefore using a bipolar setup, consisting of two electrodes placed next to each other on the same muscle. The bipolar setup works like this; the signal runs through both electrodes. The signal measured by each electrode is matched and potential differences, (e.g. noise) will be cast away. (Siriprayoonsak 2005) The reference point should be an electrically neutral place like a bony landmark (electrode) or around the angle or wrist (Strap) (De Luca 2002). In this project, a moist EMG-strap is placed around the angle.

5.8 EMG recordings

Muscular activity in the forearm was measured using a mobile system consisting of a 16 channels surface EMG acquisition system (LISin Bioengineering Center, Torino, Italy). A Rack-Mount Connector (National Instruments, Austin TX, USA) and a 16-bit USB-6121 (National Instruments, Austin TX, USA) all connected together and wired to a laptop. Mr.Kick III preview (KnL incl. Wirex support, Aalborg University, Denmark) was used for data collection. For settings, the standard gain was 2000. If necessary, the gain could be adjusted in relation to the individual subject. Within the software of Mr. Kick III preview four channels were defined, and the sample rate was set for 2000.0 Hz, figure 14.

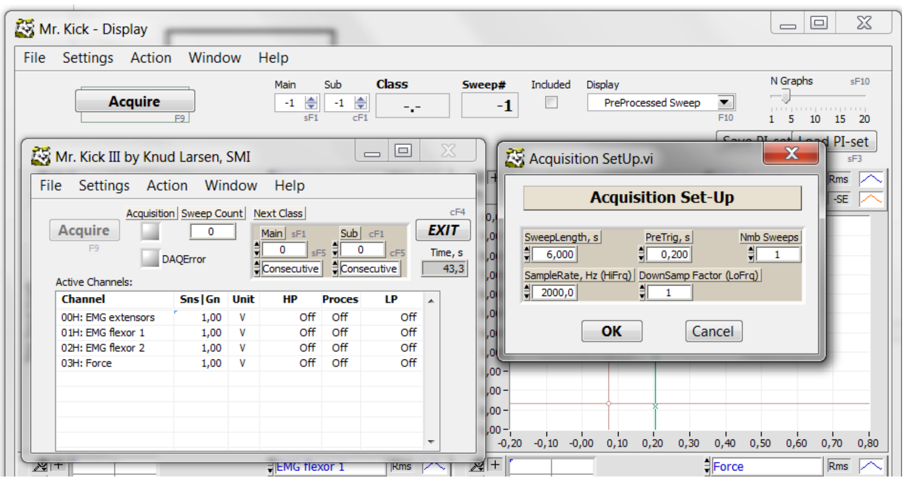

Figure 14 EMG settings in Mr. Kick (Screen shot).

As seen in figure 14, the channel 00 was the extensor and 01 and 02 was the flexor. The G200 dynamometer was also connected to the same system allowing the force generated data to be collected in Mr. Kick III preview as well, channel 03 Force, figure 14.

6. Pilot study

(Pre pilot trial: Four trials took place before the "real" pilot started, mainly to learn the equipment and test if the fixed torque needed adjustment.) The pilot study was to evaluate the test protocol for further use in the upcoming studies. Another purpose of the pilot was to get a sense of necessary sample size. Four subjects were recruited. Unfortunately one of the subjects was injured outside the experiment, so his data has been excluded. The pilot consisted of four tests placed on separate days.

- Forward grinding standard size handle (SF)
- Backwards grinding standard size handle (SB)
- Forward grinding thick size handle (TF)
- Backwards grinding thick size handle (TB)

The order of the tests was predetermined so no one performed any test in the same order. Each subject had a different order in which the tests was done, table 3.

Table 3 Pre-defined test order for each subject.

Test	Subject 1	Subject 2	Subject 3	Subject 4
# 1	SB	TB	SF	TF
# 2	TF	SF	TB	SB
# 3	SF	TF	SB	TB

The standard size handle, is a standard handle made by Harken Sailing sports equipment, to grinder pedestals. The thick was special produced by the workshop at Aalborg University. It is 20 mm thicker than the standard handle, see figure 15 for technical drawing.

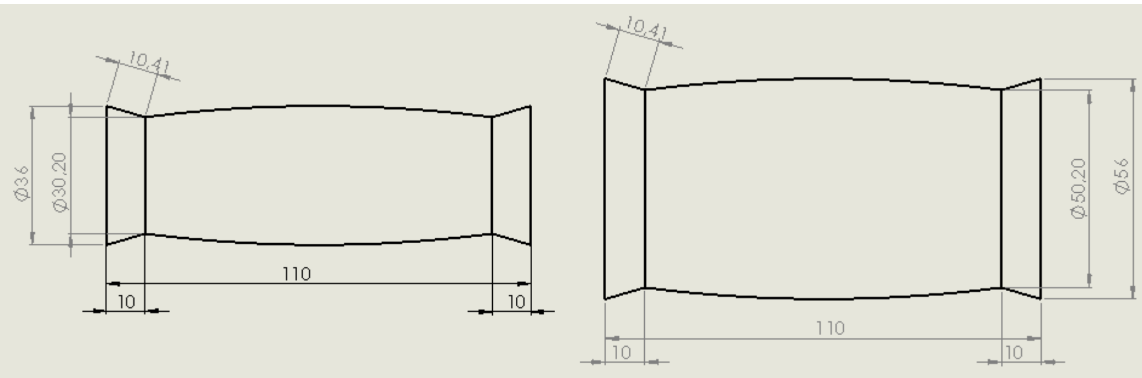

Figure 15 Original grinder handle (left) and thick grinder handle (right).

Three male subjects participated (mean ± SD age, weight, height, 24.3yr ± 1.9, 182.7cm ± 4.1, and 77.3kg ± 14.1 respectively). Subjects were unfamiliar with grinding. Furthermore, the subject's hands size were quantified as seen in figure 16. (mean ± SD hand length, hand width 18.2 cm ± 0.6 and 8.2 cm ± 0.6 respectively.

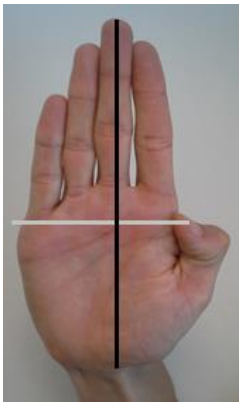

Figure 16 Hand size measurement.

The length of the hand was measured from the wrist to the distal end of middle finger, black line figure 16. The width was measured across the metacarpals, grey line figure 16.

6.1 Pilot protocol

- Calibration of the grinder, to a fixed torque of 11 Nm. Electronic equipment was setup according to chapter 5.8 (EMG recordings)
- Preparation of subject's skin using shaver and gel.
- sEMG electrodes was set up according to chapter 5.7. Forearm muscles extensor carpi radialis longus (ECR), flexor carpi ulnaris (FCU) were located by palpation while the subjects flexed or extended their wrist. (Flexor digitorum superficialis was also chosen. However due to technical errors the data was unusable.)
- Electrode and wires were fixed with tape.
- Subjects started a self-chosen warm-up/familiarization on the grinder.
- After warm-up, the subjects had a 2 min pause.
- After the pause, the subjects perform three times 5 seconds maximum voluntary contraction test (MVC), with 2 min pause.
- After the last MVC and a 2 min pause the grinding test started. Subjects held 120 RPM at fixed load until fatigued, with the selected intervention.
- Directly after grinding, an additional 5-second MVC test was performed.

6.2 Pilot data

Presentation of data from the pilot: Time to fatigue, reduction in MVC and finally the sEMG data. Data was not normally distributed and was therefore presented with median and interquartile range (IQR) values.

6.2.1 Time to fatigue

Table 4 shows time to fatigue for each subject, grinding time was longer for forward- than backwards grinding. Time to fatigue with thick handles was shorter compared to standard handle, table 4.

Table 4 Time to fatigue for each subject in four different trial. All data presented in seconds.

(N)	SF	TF	SB	TB
#1	114	105	80	51
#2	202	180	160	117
#3	107	94	81	80
Median	114	105	81	80
IQR	47,5	43	40	33

6.2.2 MVC reduction

Table 5 shows reduction in MVC for handle type and grinding direction. The loss of grip strength was bigger for both backwards settings. Power loss was bigger with thick handle compared to standard handle, table 5.

Table 5 Drop in MVC between pre- and post-test. Absolute values (Nm)

(N)	SF	TF	SB	TB
#1	-78,08	-78,08	-87,18	-56,28
#2	-59,05	-16,44	-77,07	-130,92
#3	-59,93	-77,66	-113,31	-117,50
Median	-59,9	-77,7	-87,18	-118
IQR	9,514	30,82	18,12	37,32

6.2.3 sEMG data

All sEMG data has been through signal processing. The first 10 seconds and last five seconds are excluded from analysis. The data is treated in a short time Fourier frequency of window size of 5 seconds with 50% overlap. The first and last 15 seconds of the retained data has been average out, and subtracted from each other. This will reveal if the muscles has fatigued during grinding. Data is presented with median and IQR values. Table 6 shows a table of the decrease in absolute median and mean frequency of the extensor carpi radialis longus (ECR).

Table 6 Decrease median and mean frequency for extensor carpi radialis longus (EC).

ECR	(N=3)	TB	SB	SF	TF
Mean frequency	Median value	-4,3	-0,17	2,25	2,11
	IQR	3,005	3,985	3,9355	10,04
Median frequency	Median value	-0,16	-0,01	2,01	2,38
	IQR	4,36	3,39	6,055	2,75

The median frequency showed a minor decrease in frequency for both handles in backwards grinding. The table showed approximately equal values between forward grinding, it worth noting that the median value for both mean and median frequency was positive.

Table 7 shows data for median frequency and mean frequency for flexor carpi ulnaris (FCU).

Table 7 Decrease median and mean frequency for flexor carpi ulnaris (FCU)

FCU	(N=3)	TB	SB	SF	TF
Mean frequency	Median value	-8,83	-7,22	-5,9	-6,41
	IQR	3,425	7,215	5,275	11,47
Median frequency	Median value	-7,8	-6,9	-5,41	0,84
	IQR	2,925	5,06	6,055	8,41

The results from table 7 shows a bigger decrease in mean and median frequency during backwards grinding compared with forward grinding, with the TB setting with the highest reduction in mean and median frequency. Surprisingly there was a bigger reduction in SF median frequency.

6.3 Critique of Pilot

6.3.1 MVC

The maximal grip strength test seems to be able to detect difference between settings, and reveals bigger strength loss after backwards grinding, even though grinding periods are shorter. However, 5 seconds MVC seemed unnecessarily long and should for further test be changed to 3 seconds. The idea behind the 5 seconds MVC came from Edgren, Radwin and Irwin (2004). They calculated the average between 2-4 seconds, in our experience that method really doesn't make any sense. Since the power distribution various between trials; however the peak is always the peak.

6.3.2 sEMG

There are large variances between subjects for each muscle; this is properly due to different muscle recruitment or grinding technique. Therefore, both muscles were maintained future test protocols. A larger sample is required to make any conclusion. However, the tendency of this pilot sEMG data reveals the same tendency as MVC test- that backwards grinding is more fatiguing for the forearm muscles.

6.3.3 Handle

Beside size the thick handle is also made in a different material then the original, and therefore has a higher mass. However, the project group does not believe that a change in material or weight would have had a significant effect on results.

When grasping around the original handle the thumb and index finger touches each other and the hand is there therefore more closed around it compared to the thick handle where the thumb and index finger is apart from each other, (this was the case for all subjects). This is one of the reasons to believe that fatigue will strike faster when using thick handles since it requires a higher neuromuscular recruitment, when the diameter expands (Ratamess et al. 2007) and because grip strength seems to decline when fingers start to get further apart from each other (Kong & Lowe 2005).

6.4 Final thoughts

The pilot trial was a success. The setup could detect differences between settings. In addition, results show the same tendency as in previous studies (Pearson et al. 2009), despite this being very different (e.g. strength exercises versus grinding). The hypothesis regarding forward- and backwards grinding would be that backwards grindings is affected the most, since a pulling exercise require more grip strength / endurance the pushing exercises (Ratamess et a. 2007).

7. Protocol

7.1 Study 1

The protocol will describe 'the forward- backwards grinding' experiment systematically so that others might be able to replicate if needed. The experiment contains two tests with one variable: the grinding direction.

1) System calibration and checkup

Before the subjects' arrival the grinder and electrical systems were calibrated. The grinder was set to a torque of 10.0 Nm. The height of the grinder was set to maximum, 94 cm. A gripping test was performed by the authors, to confirm if the hand dynamometer (G200 Model, Biometric Ltd., Newport, UK) was still functional. Checking the functionality of the surface electromyography (sEMG) system happened with each subject, since it required placement of electrodes on the muscles.

2) The subjects and protocol

Upon arrival, subjects got an explanation of the procedure. Afterwards they had to sign a disclaimer (appendix A) that they understood the circumstances and were doing this on their own free will.

3) Surface electromyography

Skin preparation and sEMG electrodes were placed on three muscles on their right forearm as well as a reference strap around the angle, chapter 5.7. Afterwards the subjects were instructed to flex and extend the wrist to see if the applied electrodes were a success. Should the signal not be clear, the gain was changed, if this did not solve the problem, rearranging the electrodes was step two. Next was taping the electrodes and cables making sure they stayed in place while grinding.

4) Familiarization and warm-up

Next was familiarizing and warm-up, as well as making sure that cables were fixed. The subject can grind in any direction.

5) Baseline maximal voluntary contraction

Subject did three maximal voluntary contraction (MVC) tests using a hand dynamometer (G200 Model, Biometric Ltd., Newport, UK). They were instructed to sit in an upright position, having there right arm close to their upper body in a 90 degree angle. While squeezing the subjects were not allowed to flex or extend their wrist but was to hold it in a neutral position. Three MVC test lasting three seconds each with a 2 min break in-between. For further analysis only the highest peak force from one of the three tests was taken out.

6) Forward- or backward grinding

Two minutes after the last MVC test finished, the grinding test started. The subject grinded with a cadence of 120 RPM until fatigue was reached. If the RPM was too high or low, subjects would get verbal instruction to grind faster or slower. Definition of fatigue was when the RPM could not be upheld even if instructed to grind faster. Grinding direction has been randomly decided.

7) Post-maximal voluntary contraction

Immediately after the subject finish grinding, a post MVC test was made.

X) The next test

The first part of the experiment was finished and the subjects would come back after 24-48 hours and go through the same protocol with the exception of grinding in the opposite direction.

7.2 Study 2

The protocol for study 2 was almost identical to the protocol for study 1. The difference lies in the grinding phase. The subjects had to participate in three trial, grinding with three different handle sized (32, 34 and 36 mm I diameter) in a randomized order. The subjects would only be grinding backwards based upon the results from study 1, chapter 11. In addition, the grinding settings being the torque and cadence equal to study 1. The same goes for sEMG setup, baseline MVC, and post MVC. Note: Subjects hand dimensions were measured as described in the Pilot study, chapter 6.

7.3 Study 3

Study 3 had the same protocol as study 1 with the exception of only having to grind backwards. The subjects had a custom-fit handle set each, which they had to grind with in one of the two trials. A description of the custom-fit handles, using a 3D scanner and 3D printer will be described in the following chapter 8 and 9.

8. 3D Scanning

To construct a custom-fit handle set with respect for the individual hand and finger dimensions a 3D scanning and 3D printing of a hand or a handprint could give a perfect result of customization.

3D scanning has proven itself useful in reverse engineering. Reverse engineering is one of the most important techniques in manufacturing. The technique involves measurement of an object and reconstructing it from that information. The development of 3D scanners has made this process easier and faster. Because with the scanner you can generate a 3D mesh, composed of triangles of a desired object. This 3D mesh can be modified in a CAD system. A description and evaluation of different 3D scanning systems will be presented in the following chapters.

8.1 Microsoft Kinect 3D scanner and ReconstructMe

Kinect sensor (Microsoft, Redmond, Washington, U.S.) is a camera system developed for Xbox 360 entertainment system, which allows the user to control and interact with the console without a traditional controller. (Andersen, et al. 2012; Oliveira, et al. 2013)

Kinect works together with ReconstructMe, which is a 3D scanning software. ReconstructMe supports a wide range of RGBD sensors such as the Kinect. Performing a scan with the Kinects happens by moving the camera around an object or moving an object in front of the Kinect. The scan can be exported in different CAD formats as .PLY and .OBJ. (ReconstructMe 20015)

Kinect consist of an infrared laser, infrared camera and a RGB camera. Kinect calculates depth by using a triangle process. First, an infrared laser beam is sent out, the beam is then divided creating a pattern of small dots, which are projected in the room. The infrared camera then registers the pattern. When a dot reflects from an object, the distance from the Kinects reference plane will either increase or decrease. From the reflection-information, the Kinects photo processer will calculate the depth for every pixel. As shown in figure 17 the distance calculated from the camera-laser plane and not directly from the Kinect. (Andersen et al. 2012)

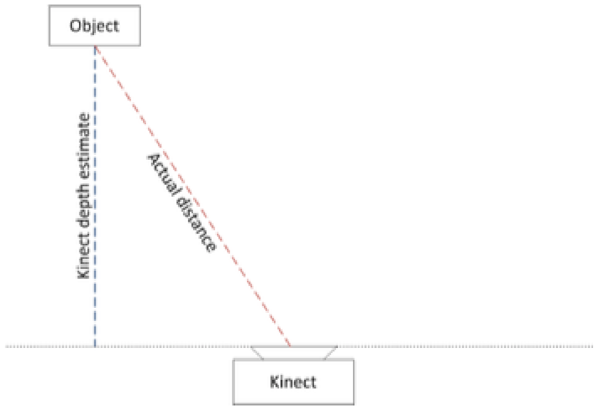

Figure 17 Kinect depth estimation ***(Andersen, et al. 2012, pp. 6)***

Kinect uses a frame rate of 30 FPS to capture depth- and color pictures. This integration of depth and color pictures results in a point cloud, which can include 300.000 points in each frame. By registering, the point-cloud the Kinect is capable of quantifying a movement or picture in 3D. (Andersen, et al. 2012) Studies have shown that the Kinect is capable of doing 3D scans, with accuracy similar to more complex and expensive 3D body-scan systems (Weiss et al. 2011; Andersen, et al. 2012). However, other studies have shown that the accuracy of the Kinect is depending on the distance to the object. The accuracy can differ 16.5 mm – 40.5 mm within the depth visual field, which is 0.8-3m. (Andersen, et al. 2012)

8.2 MakerBot digitizer turntable

MakerBot Digitizer turntable (MakerBot Industries, New York City, USA) is a 3D scanning system consisting of a RGB camera two lasers and a turning table see figure 18. (Thinglab 2013)

Figure 18 The Makerbot digitizer ***(Whitewam 2013)***

Like the Kinects system, MakerBot digitizers RGB camera is recording a point cloud from two lasers, and thereby creating a mesh. In contrast to Kinect the MakerBot Digitizer is made to scan smaller objects, because of a maximum cylindrical scan volume of 20x20 cm. A scan takes approximately nine minutes. Unlike the Kinect, MakerBot Digitizer does not require any scanning techniques, because of automatic turntable table, figure 18. One laser is turned on at a time during a 360 rotation. After the first 360° rotation (halfway through the scan) the first laser is turned off and the second turned on, and another 360° rotation completes the scan. The point cloud from each 360° rotation is then compared, and the software calculates the final mesh. (Thinglab 2013)

Another system feature is the possibility of turning the object and repeating the scan, called Multiscan, figure 19. However, Multiscan is not possible with all objects. The associated software is MakerWare for digitizer V 3.6.0.78 (MakerBot Industries, New York City, USA) and just like ReconstructMe it is possible to export the mesh in different file formats. (Thinglab 2013)

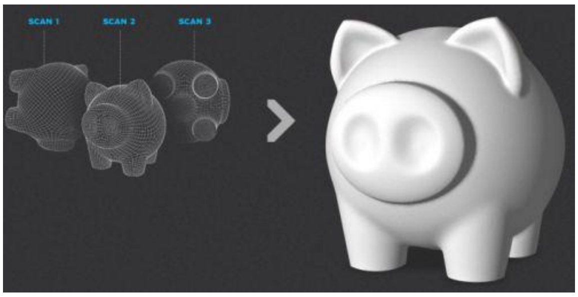

Figure 19 A 3D scan of a piggy. ***(3D printer center 2015)***

MakerBot digitizer also has some limitations; the system does not handle sharp angles, dark objects, small details, complex geometries and reflective materials that well. Some of these points can be improved either by preparing the object with a layer of baby powder or simply by spray-painting the object with another color. Both the Kinect sensor and MakerBot digitizer are very sensitive for light. This sensitivity limits the outdoors use, and works best in dark rooms. (Andersen et al. 2012)

8.3 Comparison and evaluation

The problem with the Kinect system is that it is designed as a gaming system, and not as an accurate 3D scanner. Its accuracy of 16.5-40.5 is simply not acceptable for this type of project. We have tried to perform scans with the Kinect of the hand (figure 20A) and a Play Doh model of a handprint. The handprint scan was never completed. As figure 20A shows, the scanner was not capable of capturing the fingers, so an alternative system had to be used. Since it is not possible to perform body scan with the MakerBot digitizer due to the turning table a handprint was made instead, figure 20B.

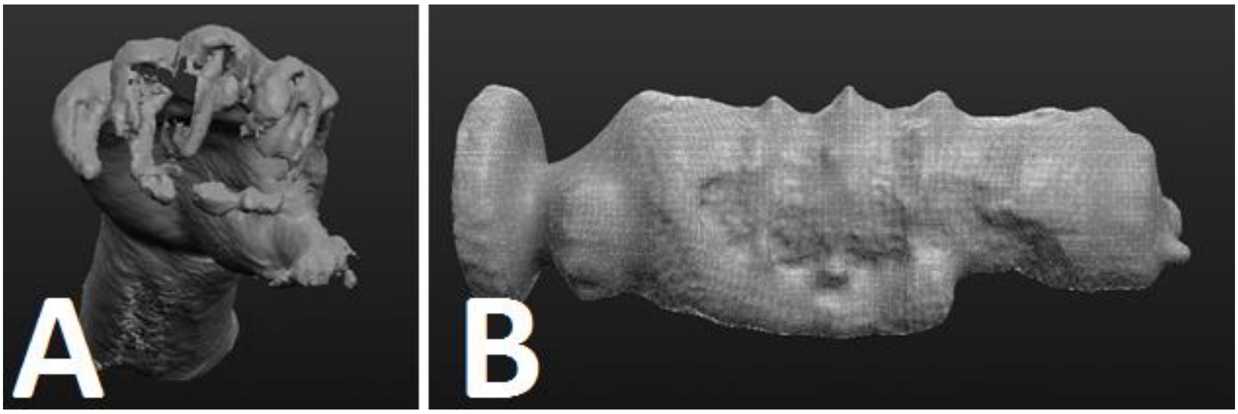

Figure 20A Hand scan made with Kinect. Figure 20B Handprint scan made with MakerBot digitizer.

Based on the scans made in practice (Figure 20A and 20B), it was decided to use the MakerBot digitizer for further handle development.

9. From concept to final product

The purpose of the next section is to give a brief description of some of the phases involved in the concept development of grinder handles. The purpose of concept development is to identify the needs of the target market. Product concepts are generated and evaluated, and one or more concepts are selected for further testing. The next section also describes the reflections behind the concept selections of this project. Additional the next will section also describe how the handle was created from handprint to final product.

9.2 Concept development

Identify customer/user needs

The purpose of this phase is to understand the customer/user needs and requirements (Ulric & Eppinger 2012).

Establish target specifications

This phase provides a description of what the product has to do. It is a translation of the customer/user needs into technical terms. (Ulric & Eppinger 2012)

- Reduce muscle fatigue in the forearm compared to existing handle.
- Fit existing grinding station
- Easy to replace
- Easy to use (Remove and put hands on)

9.3 Concept generation

The purpose of this phase is to generate concepts ideas that may address the customer/user needs. Concepts generation is a mix of external search, problem solving internally in the team and a systematic exploration of existing products that may address the customer/user needs. The result of this phase is a number of different concepts, normally represented by a sketch and a short description, figure 21. (Ulric & Eppinger 2012) See Appendix B for all concept sketches and description.

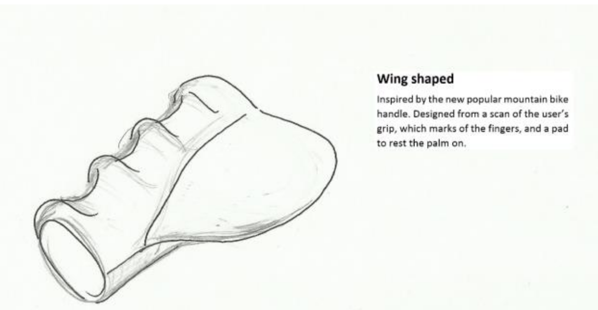

Figure 21 Sketch of the wing shaped handle.

9.4 Concept selection

The purpose of this phase is analyze the different concepts and sequentially sort out which concepts fall short of the customer/user needs while identifying the most promising concepts. (Ulric & Eppinger 2012) In table 8 each concept is rated from 1-5 in how well they cope with the target specifications, which can be determined before testing. The wing shape was the high score and has therefore been selected as the most promising concept, table 8.

Table 8 Concept rating

Concept	Customized	Easy to remove and put hands on	Easy to replace	Fit existing grinder stations	Total score
Cone	1	5	5	5	16
Wing shaped	5	4	5	5	19
brass knuckles	4	1	5	5	15
brass knuckles – no finger holes	3	2	5	5	15
Finger shaped	4	4	5	5	18

9.5 Making of handle

9.5.1Optimal handle diameter

Three subjects from study 2 were recruited for this customization study. By using subjects from study 2 an optimal diameter for the individual was decided beforehand. All three subjects has an optimal diameter at 32 mm. Kong and Lowe (2005) found that each finger should be taking into account when creating a handle, chapter 4.4.

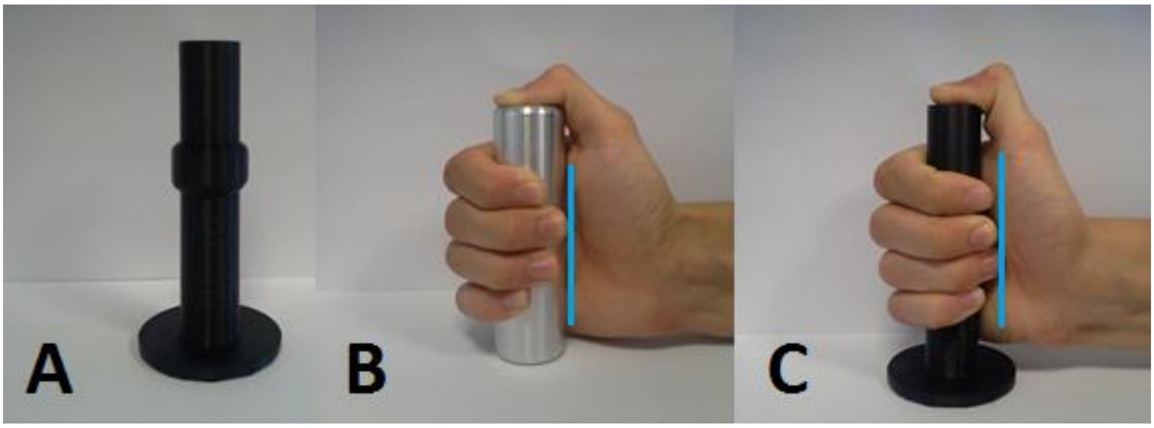

Figure 22A 3D printed pedestal and core object for customization, 22B grip around the 32mm handle, 22C grip around the pedestal.

The 3D printed handle core in figure 22A is 32 mm in diameter only where the middle finger is placed. The rest of the handle core is 25 in diameter. Creating a cylinder that does not have the same diameter across its length will optimize the total grip strength, since each finger now works within their optimal diameter (Kong & Lowe 2005). When comparing a cylindrical handle (figure 22B) to the custom made one (figure 22C) note that the index, ring and little finger are more aligned with the middle finger (figure 22C). This should, in theory give a higher absolute value in grip strength since each finger now work at proper length (Kong & Lowe 2005). Meaning that the finger flexors for index, ring and little finger are no longer as far stretched beyond optimal working range (Amis 1987; Fowler et al. 2001; Seo & Armstrong 2008).

9.5.2 Play-Doh

After the optimal handle diameter was determined. A thin layer of play-doh was applied around the handle core, figure 23A. Subjects were instructed to squeeze around the handle until they could feel the handle core, figure 23B. When the subjects release their grip, a final handprint would be left in the play-doh, figure 23C)

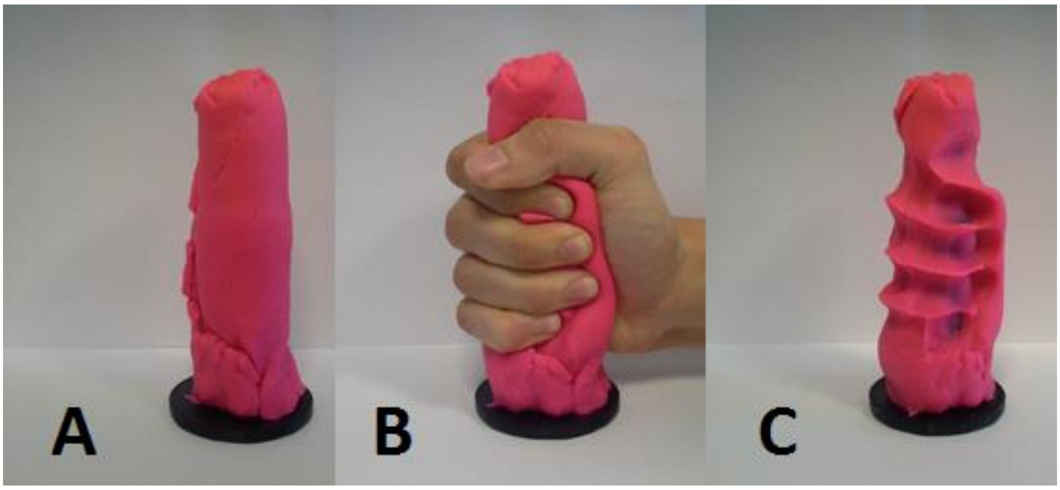

Figure 23 Three steps illustrating the making of the customized handles. A) Play-duh wrapping, B) Gripping around the play-duh, C) Final hand print.

9.5.3 3D Scan

The play-doh print was scanned with MakerBot Digitizer turntable (MakerBot Industries, New York City, USA), where the cylinder was placed within the center of the turning table, figure 24A.

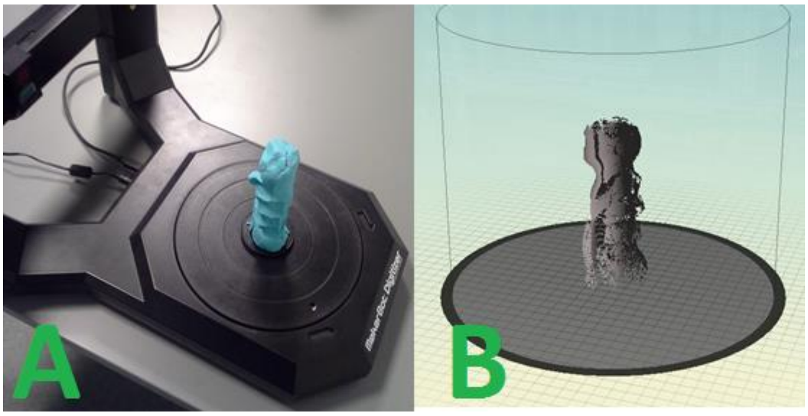

Figure 24A the handprint placed on the turning table ready for scanning. 24B a screen shot of the scanning within the software.

Dark environments and light colored play-doh was used for best results. Because of the handle shape, the MakerBots multiscan function was not possible. Files can be exported as a mesh in different file formats, but .obj was chosen because it is recruited in the next step. Figure 24B shows how the scan looks upon completion.

9.5.4 Sculptris

Sculptris v.Alpha-6 (Pixologic Inc., California, USA) is a virtual free-ware sculpting software, based on the concepts of clay modeling. The user can push, pinch, pull, twist or smoothen virtual clay or import mesh, figure 25.

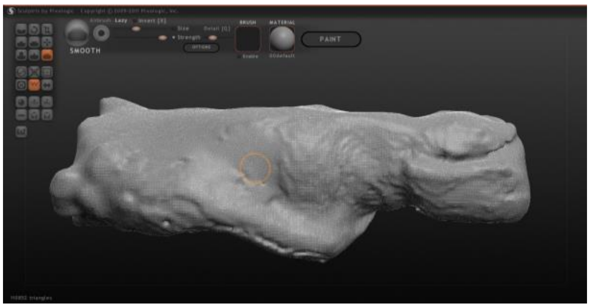

Figure 25 imported 3D scan of the handprint into Sculptris (Screen shot).

Sculptris was used to smoothen and flatten the surface of the handle to eliminate eventual spikes and Irregularity, figure 25.

9.5.5 SolidWorks

SolidWorks CAD software v.2013x64 Edition SP05 (Dassault Systèmes SolidWorks Corp., Massachusetts, USA) is a solid modeling computer aided design (CAD) software and uses a parametric feature-based approach to create models. Traditionally the user has to start a model with creating a sketch in 2D and hereafter make a 3D model. It is not necessary to start from scratch, since a 3D scan of the handle had already been made. The mesh was imported into SolidWorks and processed with the surface wizard, which is found in the Scanto3D toolbox. Here is surface generation done, in which any undescribed areas are described, done by deleting lines, adding lines, moving points or slacking lines, figure 26.

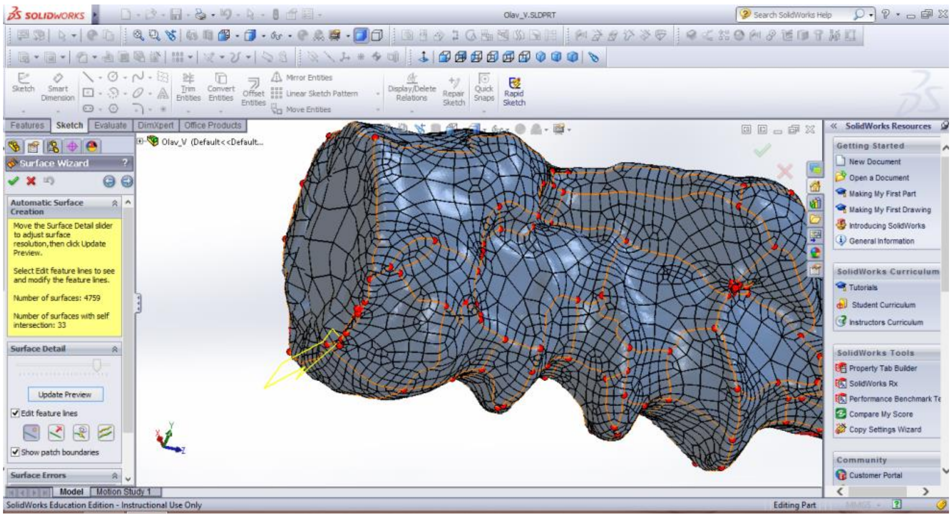

Figure 26 Correcting unknown mesh areas (Screen shot).

The process can be evaluated by hitting "preview" and this process is repeated until all areas are described. When this process is done the mesh is successfully imported as a solid. Now is it possible to apply features to the model. Starting out, a hole through the center of the handle is made. This is done by drawing a sketch and using the hole-feature (22.2 mm). Hereafter the handle is adjusted to the proper length, 110 mm. This is done by applying two planes with 110 mm between each. Hereafter the body is split and the delete feature used.

9.5.6 3D print

3D printing: a manufacturing form in which a digital file is translated into a physical object through a 3D printer. The approach that 3D printers use is to build layer upon layer. The first 3D printer was invented in 1984. (PCMag 2015) Despite that 3D printing has been around for a few decades, it is only recently that it has started to become more accessible. This development is partly due to the first patents in the field beginning to expire. (Strömbäck

2013) 3D print differentiates itself from other manufacturing techniques in that it does not require shapes for example Injection molding, and almost any shape can be printed. In this projects the MakerBot Replicator 2X (MakerBot Industries, Brooklyn, NY, USA) is used to create the custom-fit handles. The 3D printer is constructed as a closed box with special features to ensure a steady print. The printed product is made out of ABS plastic. The 3D prints start by printing the bottom of the object and then placing new material upon the old resulting in a product with minimal waste. (MarkerBot 2015)

9.6 Concepts testing

In this phase one or more concepts will be tested to verify that the customer/user needs has been fulfilled. Another purpose of this phase is to identify any shortcomings that must be reassessed during further development. (Ulric & Eppinger 2012) In this case the product will be compared with an existing handle - to evaluate if the target specification of reducing forearm fatigue is met.

10. Results: Study 1 - Forearm fatigue during forward and backwards grinding

In this section, will all data from study 1 be presented and analyzed. Different statistical test will be used to investigate potential differences between the two grinding directions.

10.1 Descriptive statistics

Table 9 present the descriptive data for the eight subjects whom participated in study 1.

Table 9 Descriptive statistics; mean and SD values for age, height, weight, hand length and width.

(N=8)	Mean	SD
Age	24.7	1.4
Height	182.7	5.8
Weight	77.4	11.2
Hand length	18.7	1.1
Hand width	8.5	0.4

The eight subjects represent a relatively homogenous group since standard deviation is relative small in all five attributes see table 9.

10.2 Time to fatigue and MVC

Data was tested for normality, assessed by Shapiro-Wilk test (P>.05), see table 10.

Table 10 Test for normality regarding Time, Absolute and Relative MVC drop, using Shapiro-Wilk test.

Shapiro-Wilk test	(N=8)	Sig.
Time to fatigue	Forward	0.129
	Backwards	0.140
Absolute MVC drop	Forward	0.425
	Backwards	0.151
Relative MVC drop	Forward	0.899
	Backwards	0.167

Table 11 present the descriptive data regarding Time, Absolute and Relative MVC drop in form of mean value and standard deviation.

Table 11 Descriptive statistics presenting mean and SD values for Time, Absolute and Relative MVC drop.

(N=8)	Direction	Mean	±SD
Time to fatigue	Forward	127.3 s	41.6 s
	Backwards	92.0 s	31.2 s
Absolute MVC drop	Forward	- 46.6 N	27.6 N
	Backwards	-96.1 N	27.03 N
Relative MVC drop	Forward	91.9 %	4.6 %
	Backwards	84.3 %	5.1 %

As seen in table 11 each data set (Time, Absolute or Relative) is divided in two groups being the grinding direction, forward or backwards.

Figure 27 shows bar plot of mean and SD for each direction of grinding.

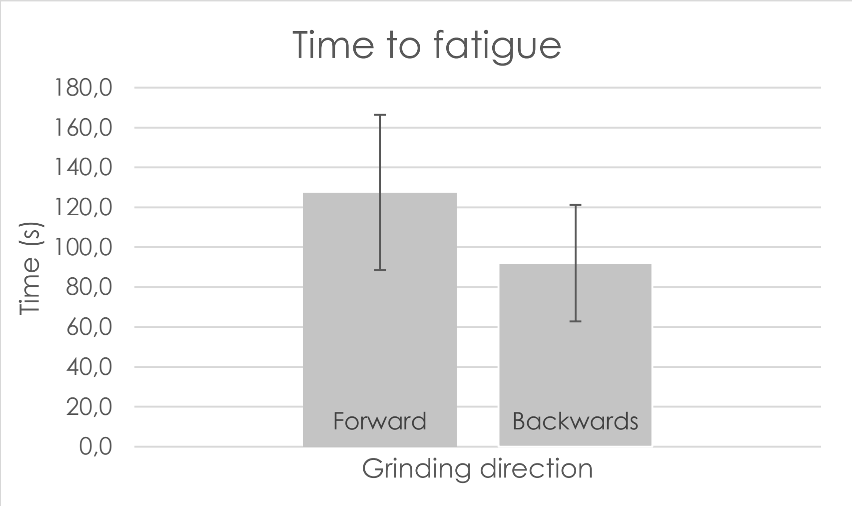

Figure 27 Time to fatigue in different directions scaled in seconds (s).

Table 12 present statistical data using a Paired t-test. Paring the directions forward and backward. One test for each data set; Time to fatigue, Absolute and Relative MVC drop.

Table12 Pared t-test between grinding direction; Forward and backwards.

Paired t- test (N=8)	Mean difference	t value	Sig. (2-tale)
Time to fatigue Forward - Backwards	35.3±40.8 s	2.451	0.04*
Absolute MVC Forward - Backwards	49.57 ±48.1 N	2.914	0.23*
Relative MVC Forward - Backwards	7.5 ± 9.1 %	2.351	0.05*

There is a statistical significant different between directions then looking at time, absolute and relative MVC. All three tests are significant since *p*-value is *p*=<0.05, table 12. The relative MVC data is also displayed in figure 28 below.

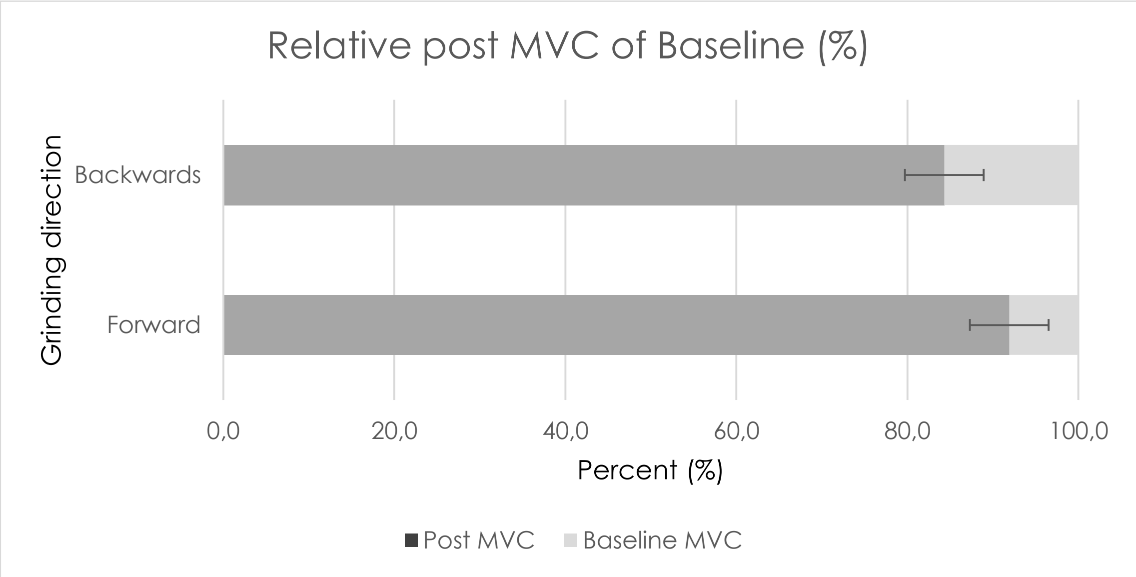

Figure 28 Relative post to MVC of baseline for each direction (Backwards and forward) presented in percent (%).

10.3 sEMG

There has been calculated mean- and median frequency for the first and last 20 seconds, and 30 seconds. However, statistical analyses continued with the 20 seconds windows since that showed bigger difference between start and end frequency.

Two-way ANOVA with repeated measurement was conducted to investigate if there was statistically significant differences between the first 20 seconds and last 20 seconds in RMS, mean and median frequency. Data was normally distributed, assessed by Shapiro-Wilk test ($P>.05$), table 13. Shapiro-Wilk for the difference in frequency of the first and last 20 seconds of grinding

Table 13 Descriptive data regarding sEMG data for extensor carpi radialis longus (EC) and flexor carpi ulnaris (FCU) in both grinding directions. Presented in mean-, median frequency and RMS.

(N=8)	Direction	Muscle	Sig.			
			First 20 s	Last 20 s	Difference	
					Absolut	Relative
Mean frequency	Forward	ECR	0.187	0.390	0.687	0.320
		FCU	0.841	0.982	0.055	0.076
	Backwards	ECR	0.265	0.747	0.212	0.419
		FCU	0.632	0.437	0.448	0.407
Median frequency	Forward	ECR	0.115	0.700	0.933	0.597
		FCU	0.936	0.875	0.368	0.078
	Backwards	ECR	0.194	0.171	0.439	0.366
		FCU	0.857	0.672	0.614	0.759
RMS	Forward	ECR	0.695	0.103	0.499	0.722
		FCU	0.425	0.105	0.650	0.916
	Backwards	ECR	0.262	0.144	0.972	0.435
		FCU	0.367	0.077	0.862	0.424

10.3.1 Mean Frequency

Forward grinding

Results from a Two-way ANOVA with repeated measurements showed statistically difference between median frequency of the start and end measurement for forward grinding $F(1,7) = 12.07$, $p = 0.01$, partial $\eta = 0.633$. See table 14 for mean ± SD. Post hoc analysis with Bonferroni revealed that median frequency was statistically significant decreased for both muscles with a mean difference of 7.631 ± 2.19 standard error, $p = 0.01$.

Backwards grinding

Results from a Two-way ANOVA with repeated measurements showed statistically difference between median frequency of the start and end measurement for backwards grinding $F(1,7) = 44.687$, $p < 0.001$, partial $\eta = 0.855$. See table 14 for mean and SD. Post hoc analysis with Bonferroni revealed that median frequency was statistically significant decreased for both muscles with a mean difference of 6.53 ± 2.74 standard error, $p = 0.049$.

10.3.2 Median Frequency

Forward grinding

Results from a Two-way ANOVA with repeated measurements showed statistically difference between median frequency of the start and end measurement for forward grinding $F(1,7)=10.508$, $p=0.014$, partial $\eta = 0.600$. See table 14 for mean ± SD. Post hoc analysis with Bonferroni revealed that mean frequency was statistically significant decreased for both muscles with a mean difference of 7.573 ±2.33 standard error, $p = 0.014$.

Backwards grinding

Results from a Two-way ANOVA with repeated measurements showed statistically difference between median frequency of the start and end measurement for backwards grinding $F(1,7)=31.675$, $p=0.001$, partial $\eta = 0.819$. See table 14 for mean and SD. Post hoc analysis with Bonferroni revealed that mean frequency was statistically significant decreased for both muscles with a mean difference of 6.987 ± 2.467 standard error, $p = 0.025$.

10.3.3 RMS

Forward

Results from a Two-way ANOVA with repeated measurements showed a statistically difference between RMS of the start and end measurement for forward grinding $F(1,7) = 7.296$, $p = 0.031$, partial $\eta = 0.510$. See table 14 for mean ± SD. Post hoc analysis with Bonferroni revealed that mean frequency was statistically significant decreased for all three muscles with a mean difference of 0.278 ± 0.032 standard error, $p = 0.032$.

Backwards

Results from a Two-way ANOVA with repeated measurements showed no statistically difference between RMS of the start and end measurement for backwards grinding $F(1,7) = 4.604$, $p = 0.069$, partial $\eta = 0.397$. See table 14 for mean and SD. Additionally did paired t test not reveal any significant difference between the start and end value of RMS for either of the muscles. Extensor carpi radialis longus (ECU) $t(7)=2.15$, $p= 0.68$, flexor carpi ulnaris (FCU) $t(7)=-1.856$, $p=0.106$.

Table 14 sEMG results from a Two-way ANOVA with repeated measurements. Presented in mean-, median frequency and RMS. sEMG was measured upon extensor carpi radialis longus (ECU) and flexor carpi ulnaris (FCU).

(N=8)	Direction	Muscle	First 20s Mean ± SD	Last 20s Mean ± SD	Absolut Mean diff ± SD	Relative Mean diff ± SD
Mean frequency	Forward	EC	102.9 ±21.4	96.1 ± 18.1	-6.86 ± 8.89	0.93±0.08
		FCU	93.4 ± 15.7	82.8 ± 12.9	-10.56 ± 5.93	0.89±0.06
	Backwards	ECR	94 ± 13.7	83.3 ± 10.9	-10.72 ± 8.05	0.89±0.08
		FCU	88.1 ± 15.6	76.12 ± 10.1	-12.06 ± 8.35	0.87±0.07
Median frequency	Forward	ECR	89.7 ± 23.8	83.0 ± 19.9	-6.75 ± 9.18	0.93±0.09
		FCU	75.6 ± 14.2	67.2 ± 10.9	-8.38 ± 5.86	0.89±0.07
	Backwards	ECR	77.7 ± 11.0	67.0 ± 9.9	-10.70 ± 8.81	0.86±0.10
		FCU	70.4 ± 14.4	60.4 ± 9.4	-10.08 ± 8.04	0.86±0.09
RMS	Forward	ECR	0.24 ± 0.06	0.38 ± 0.17	0.134 ± 0.145	1.53±0.49
		FCU	0.49 ± 0.09	0.68 ± 0.25	0.189 ± 0.145	1.37±0.33
	Backwards	ECR	0.44 ± 0.20	0.56 ± 0.30	0.112 ± 0.084	1.25±0.27
		FCU	0.79 ± 0.29	0.94 ± 0.33	0.143 ± 0.218	1.20±0.22

10.3.4 Difference between first and last 20s of grinding

Two-way ANOVA for the absolute and relative difference for the first and last 20s of grinding showed no statistically difference for either forward or backwards in mean-, median frequency or RMS. See appendix C for tables.

11. Results: Study 2 – Handle diameter influence on forearm muscle fatigue during backwards grinding

In this section, will all data from study 2 be presented and analyzed. Different statistical test will be used to investigate potential differences between the three grinding handles.

11.1 Descriptive statistics

Table 15 present the descriptive data for the eight subjects whom participated in study 2.

Table 15 Descriptive subject data.

N=10	Mean	SD
Age	24.6	1.4
Height	181.3	6.8
Weight	76.5	11.0
Hand length	18.6	1.1
Hand width	8.4	0.6

The ten subjects represent a relatively homogenous group since the standard deviation is low in all five attributes table 15.

11.2 Time to fatigue and MVC

Before running statistical tests on the time and MVC data, was data tested if it was normally distributed, assessed by Shapiro-Wilk test (P>.05), table 16.

Table 16 Test for normality using Shapiro-Wilk test

Shapiro-Wilk test	(N=10)	Sig.
Time to fatigue	32 mm	0.031
	36 mm	0.163
	40 mm	0.016
Absolute MVC drop	32 mm	0.212
	36 mm	0.427
	40 mm	0.655
Relative MVC drop	32 mm	0.597
	36 mm	0.831
	40 mm	0.901

Time to fatigue was not normally distributed and presented with median and IQR values, table 17.

Table 17 present the descriptive data for Time to fatigue (Median and IQR), Absolute and Relative MVC (Mean and Standard divination).

Table 17 Descriptive data for Time to fatigue, Absolute and Relative MVC.

(N=10)	Handle diameter	Median	IQR
Time to fatigue	32 mm	91	13
	36 mm	81	27.25
	40 mm	81.5	16
		Mean	±SD
Absolute MVC drop	32 mm	-60	22.54
	36 mm	-89.3	40.67
	40 mm	91.44	29.8
Relative MVC drop	32 mm	0.9	0.03
	36 mm	0.85	0.06
	40 mm	0.84	0.05

11.2.1 Time to fatigue

A Friedman test showed a statistically significant difference in time to fatigue among the handle sizes $X^2(2)=13.4$, $P=0.001$. Post hoc analysis with Wilcocin signed-rank test was conducted and found a statistical difference between 32 mm and 36 mm ($Z=-2.296$, $P=0.022$) and 32 mm and 40 mm ($Z=-2.805$, $P=0.005$) However there was no statistical difference between 36mm and 4 0mm ($Z=-1.887$, $P=0.059$). Figure 29 illustrates time to fatigue for the three handle sizes.

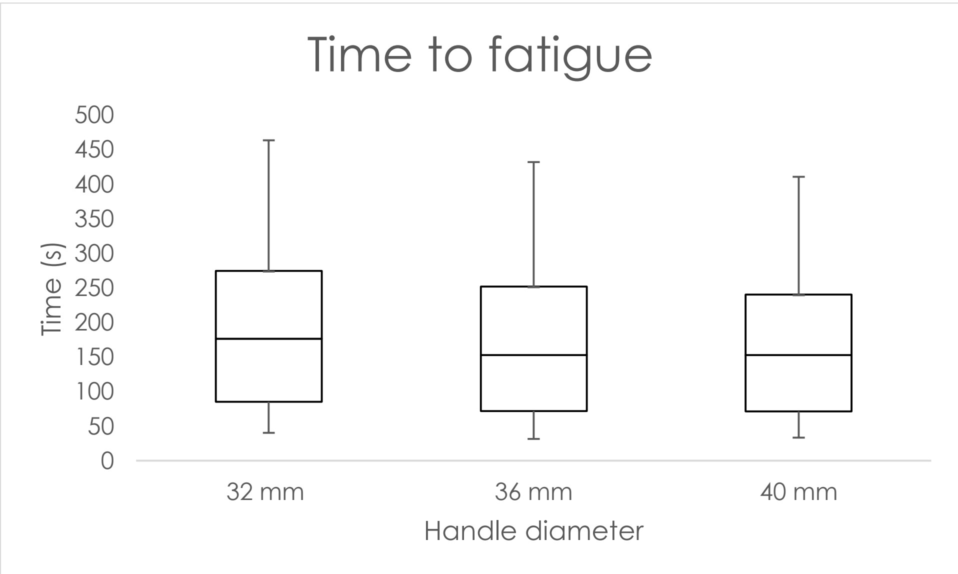

Figure 29 Time to fatigue in relation to the three handle sizes, 332, 36, and 40 mm.

11.3.2 MVC

Absolute

Results from a Two-way ANOVA with repeated measurements showed statistically difference in MVC drop between handle size $F(2,18) = 3.702$, $P=0.045$, partian $n^2=0.291$. Post hoc test using the Bonferroni correction recalled that there was a difference between 32mm and 40 mm (mean difference 31.4N ± 8.2 standard error, p=0.013), however there was no statistical difference between 32mm and 36mm (29.3N ± 14.0 standard error, p=0.200) and 36 and 40mm (mean difference of 2.1 N ± 15.3 standard error, p= 1.0).

Relative

Results from a Two-way ANOVA with repeated measurements showed statistically difference in MVC drop between handle size $F(2.18) = 4.076$, P= 0,035, partian $n^2=0.312$. Post hoc test using the Bonferroni correction recalled that there was a difference between 32mm and 40 mm (5.1% ± 1.4 standard error, p=0.018). However, there was no statistical difference between 32mm and 36 (4.9% ± 2.1 standard error, p=0.137), and 36 and 40mm (0.02% ± 2.4 standard error, p= 1.0), figure 30.

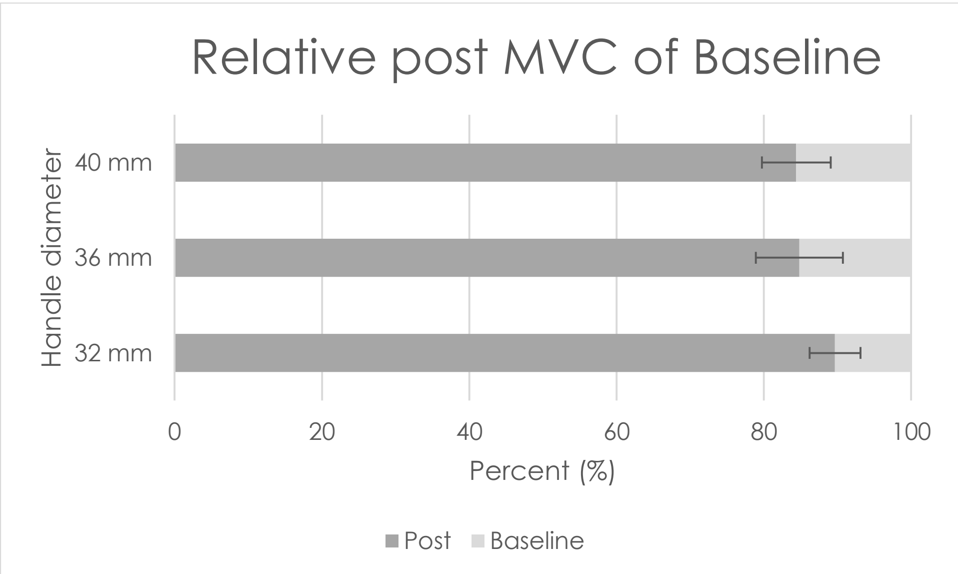

Figure 30 Relative post MVC percentage of baseline.

11.3 Surface electromyography

RMS, mean and median frequency have been calculated for all data, and statistic have been calculated, neither parameter differed, so only statistics from median frequency is presented. Table 18 shows results from shipiro wilk test, p>0.05, all data is normally distributed.

Table 18 Descriptive sEMG date using shipiro wilk test. Measured muscles: Extensor carpi radialis longus (ECR) and flexor carpi ulnaris (FCU)

(N=10)	Handle diameter	Muscle	Sig.			
			First 20 s	Last 20 s	Difference	
					Absolut	Relative
Median frequency	32 mm	ECR	0.346	0.7	0.787	0.595
		EFU	0.332	0.49	0.326	0.601
	36 mm	ECR	0.078	0.07	0.979	0.229
		EFU	0.677	0.549	0.107	0.079
	40 mm	ECR	0.265	0.855	0.574	0.841
		EFU	0.672	0.824	0.272	0.31

11.3.1 Median frequency

Table 19 show mean ± SD for median frequency. During the first and last 20 seconds. Presented in Absolute and relative values.

Table 19 Median frequency for extensor carpi radialis longus (ECR) and flexor carpi ulnaris (FCU).

(N=10)	Handle Diameter	Muscle	Mean ± SD			
			First 20s	Last 20s	Absolut	Relative
Median frequency	32 mm	ECR	61.1 ± 11.9	57.4 ± 10.1	-3.72 ± 7.76	94.8 ± 11.8
		FCU	63.9 ± 12.0	58.2 ± 10.0	-5.76 ± 5.38	91.5 ± 7.7
	36 mm	ECR	70. ± 22.3	66.0 ± 16.8	-4.89 ± 7.75	94.8 ± 10.1
		FCU	67.1 ± 11.2	61.7 ± 9.4	-5.76 ± 5.41	92.3 ± 4.4
	40 mm	ECR	70.1 ± 16.3	63.3 ± 11.1	-6.79 ± 10.22	92.0 ± 12.3
		FCU	68.0 ± 10.1	62.0 ± 8.5	-6.03 ± 6.64	91.6 ± 8.5

Difference between start and end of grinding

32 mm

Results from a Two-way ANOVA with repeated measurements showed statistically difference between median frequency of the start and end measurement for grinding with the 32 mm handle $F(1,9) = 6.389$, $p = 0.032$, partial $\eta = 0.415$. See table 19 for mean ± SD. Post hoc analysis with Bonferroni revealed that mean frequency was statistically significant decreased for both muscles with a mean difference of 4.748 ±1.878 standard error, $p = 0.032$.

36 mm

Results from a Two-way ANOVA with repeated measurements showed statistically difference between median frequency of the start and end measurement for grinding with the 36mm handle $F(1,9) = 12.927$, $p = 0.006$, partial $\eta = 0.590$. See table 19 for mean ± SD. Post hoc analysis with Bonferroni revealed that mean frequency was statistically significant decreased for both muscles with a mean difference of 5.140 ±1.430 standard error, $p = 0.006$.

40 mm

Results from a Two-way ANOVA with repeated measurements showed statistically difference between median frequency of the start and end measurement for grinding with the 36mm handle $F(1,9) = 6.424$, $p = 0.032$, partial $\eta = 0.416$. See table 19 for mean ± SD. Post hoc analysis with Bonferroni revealed that mean frequency was statistically significant decreased for both muscles with a mean difference of 6.413 ± 2.530 standard error, $p = 0.032$.

Difference between handles

Absolute difference

Results from a Two-way ANOVA with repeated measurements showed statistically difference between median frequency between the handles $F(2,18) = 0.324$, $p = 0.728$.

Relative difference

Results from a Two-way ANOVA with repeated measurements showed statistically difference between relative median frequency between the handles $F(2,18) = 0.182$, $p = 0.835$, figure 31 and 32.

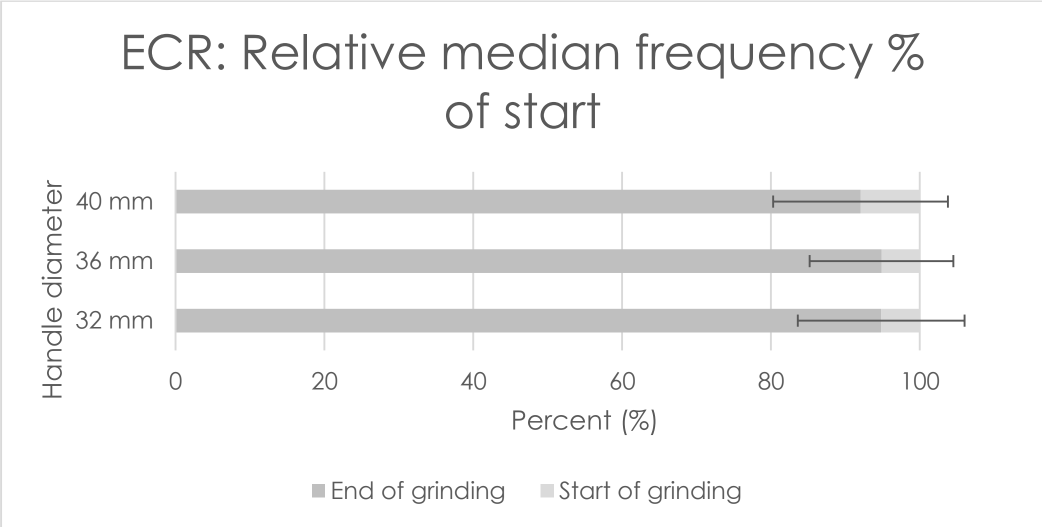

Figure 31 Percentage of start median frequency. Extensor carpi radialis longus (ECR).

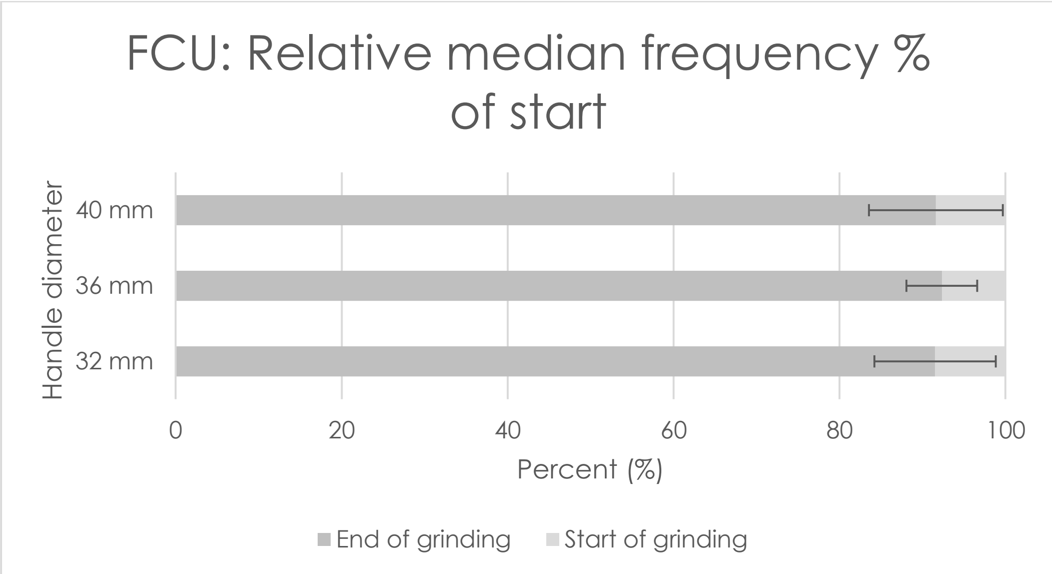

Figure 32 Percentage of start median frequency. Flexor carpi ulnaris (FCU)

12. Results: Study 3 - Design of a subject-specific grinding handle: from 3D-scanning to 3D-printing techniques – a technical note

In this section, all data from study 3 will be presented. All data are presented with median and interquartile range.

12.1 Descriptive statistics

Table 20 present the descriptive data for the eight subjects whom participated in study 3.

Table 20 Descriptive subject data.

N=3	Mean	SD
Age	24.3	0.5
Height	177.7	2.1
Weight	66.6	2.4
Hand length	18.4	0.6
Hand width	8.5	0.4

The three subjects represent a relatively homogenous group since the standard deviation is low in all five attributes table 20.

12.2 Handles

Since study three is a technical note, the final creation of the custom-fit (CH) handles is a result. Figure 32 present the handles while being printed.

Figure 32 Three set of 3D printed handles.

13.3 Time to fatigue and MVC

In table 21 is the median and interquartile range of the time to fatigue and relative decrease of post MVC from presented. Both parameters was similar. However, time to fatigue was longer with custom-fit handles (CH) and the decrease in MVC was also smaller with CH.

Table 21 Median and Interquartile range using standard handles (SH) or custom-fit handle (CH).

	Handle	Median	Interquartile range
Time to fatigue	SH	170 s	144.5 to 188 s
	CH	173 s	148 to 190.5 s
Relative MVC	SH	85.4 %	84.2 to 88.2 %
	CH	87.3 %	85.4 to 88.6 %

12.4 Electromyography

In table 22 is the relative drop in median frequency from the start of grinding to the end. ECR and FCU drop in frequency is close to each other. However is there a 6% difference between the median values of FDS.

Table 22 sEMG data, median frequency drop, percentage of baseline.

Muscle	Handle	Median (%)	Interquartile range (%)
ECR	SH	90.2	90.2 to 93.6
	CH	88.6	86.8 to 92.6
FCU	SH	79.7	78.7 to 83.2
	CH	80.2	73,8 to 89.3
FDS	SH	72.6	70.7 to 84.5
	CH	78.6	74.8 to 88.8

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Appendix

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Appendix A

Information for participants

Study 1

The following information are provided, because you have volunteered to participate in a study, towards developing a new handle type for Grinders in the America's Cup. The experiments is a part of a Master's thesis in Sports Technology at the Department of Health Science Technology at Aalborg University. In the following text are all the information about the experiment, relevant for you, be described. It is important that you read and understand the information provided. If you have any further questions, please do not hesitate to contact us.

Project title

Concept development of custom made handles for America's Cup grinders

Investigators

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Time and location

The experiments will be undertaken from the 20^{th} to the 26^{th} April. At the Sports laboratory at Niels Jernes Vej 14.

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Introduction

America's Cup is the most prestigious sail sport completion. The most physical demanding task onboard an America's cup boat is grinding (hand cycle), this is necessary to create pressure in the hydraulic system onboard, which is used to move all moving parts on the boat, such as raise and lowering the dagger boards. It's forbidden to use motors and stored energy - which means that all power has to be produced then needed, resulting in that the grinders has to be able to generate up to 700W of power in short burst, and have a normal power production around 300W.

Nevertheless, grinders have problems with forearm fatigue, even after short periods of sailing witch might be due to poorly ergonomically designed handles. Therefore, the purpose of this study is to make an optimization of the handles, by custom made handles to the specific grinder, using 3D scanning techniques and 3D printing. We will perform different test to determine the most optimal thickness of the handles and the best shape.

This is the first test, were eight subjects has been recruited to perform forward and backwards grinding, with standard handle.

The experiment consist of two trials on separate dates

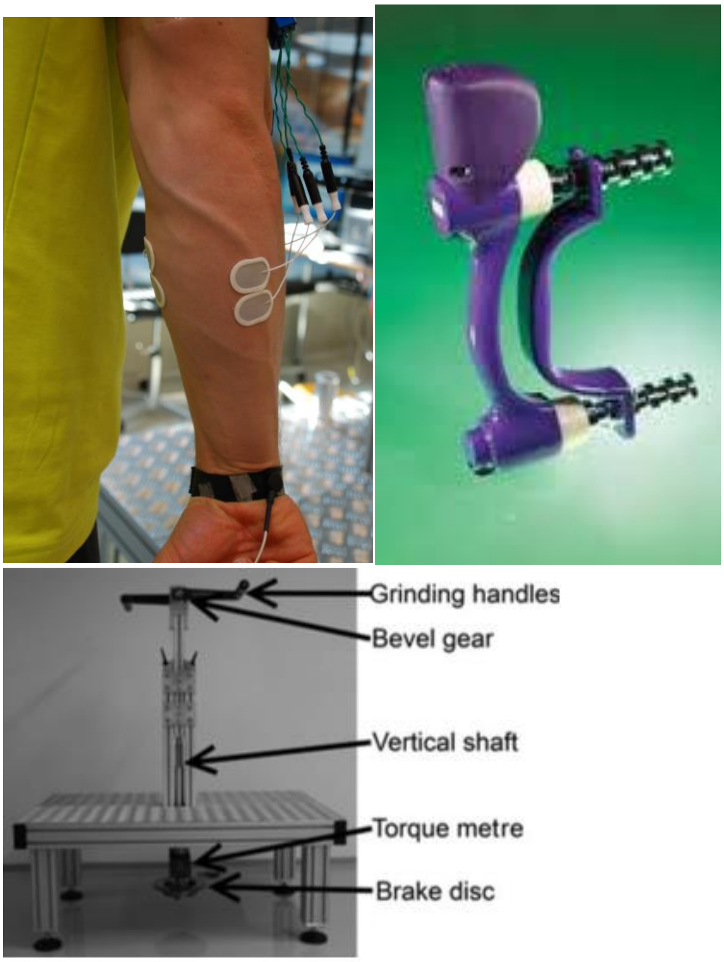
- Forward grinding
- Backward grinding

Each test take approximately 30 minutes each.

Experimental procedure

During the experiment will surface electromyography (EMG) be measured on three forearm muscle (Extensor carpi radialis longus muscle, Flexor carpi radialis muscle and Flexor carpi ulnaris muscle). Before placing electrodes on your arm, is it necessary to prepare your skin to guarantee a good signal. This preparation consist of removing hair from the measurement area with a shaver, and after that will a special gel be used to clean the area. After the electrodes and wires are attached, will you be able to have a warmup/habituation to the grinder, after that, will the experiment start. You will first perform three 3s maximal voluntary contraction (MVC) test, with 2 minutes pause between trials. The MVC test is a five seconds test where you squeeze as hard, as you can on a special handle, which measures your grip strength. After these test will you be grinding as long as possible on the grinder at 120 RPM, at a fixed load. Then you are not able to keep 120 RPM anymore, will you be stopped and perform one final MVC test.

The direction and handle size/type during grinding will vary between trials.



EMG sensors / MVC handle / Grinder station

Participant inclusion- and exclusion criteria

In order to be included in the experiments, participants have to meet the following:

- No abnormalities in bone structure or muscles in the upper body
- No injuries to the upper extremities at the time of data collection

Accessibility and publication

The data collected will take part in a Master's thesis, which will be made puplic through Aalborg University. Additionally, can the results of the study potentially be published in an article in a scientific journal and/or conference.

Benefits associated to participation

You will not receive any compensation for your participation. While the results if this research may benefit the scientific community, can we not guarantee that you will receive any personal direct benefits.

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Participant rights

Your participation is voluntary and you are free to withdraw your participation at any time. We will not take responsibility for any accidental injury or discomfort you may experience during the experiments.

Practical information

Please bring a T-shirt to the test

Consent form

Participant name:

____

I acknowledge that:

1. I have read and understood the provided information, and agree to the purpose, methods and demands of the study.
2. I have been informed that I am free to withdraw from the study at anytime without prejudice
3. My personal information will be treated anonymously
4. The results of the study will be published by Aalborg University, and may, additionally, be published in a scientific journal and/or conference.
5. Participatin is vouluntary and I will not receive any compensation
6. The project is for research purpose and may not be direct benefit to me.
7. I hereby give consent to participate in the study and I am aware that participation is at my own risk.

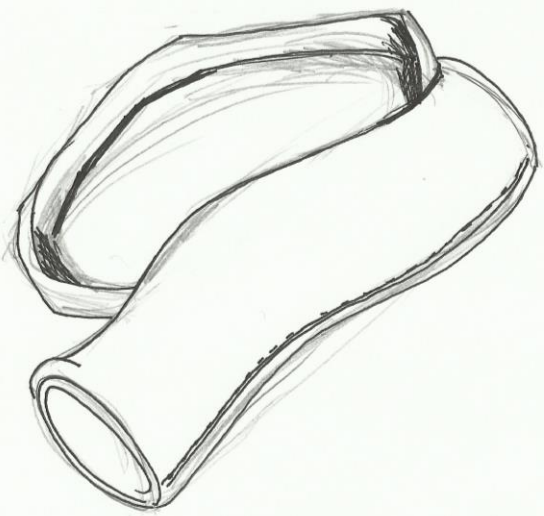
Participant: ____ Date:_________________

Investigator:____ Date:_________________

Appendix B

The cone

'The cone' has been inspired by the facts that the grip diameter should vary across the longitudinal axial to achieve higher force output at the same time putting less strain on the shorter fingers. (Kong & Lowe 2005)

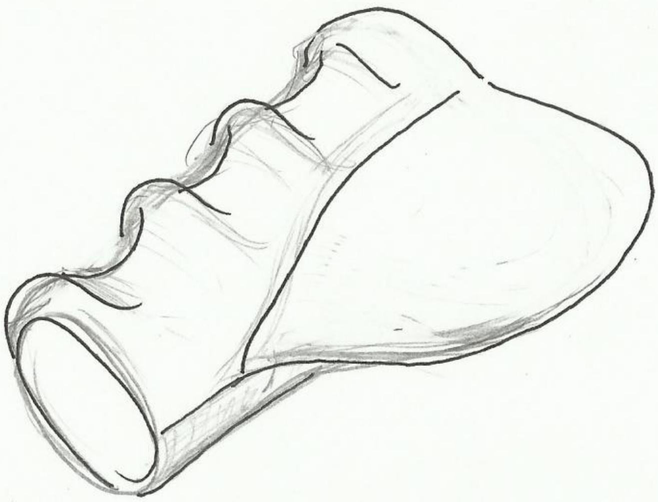


Locked hand

The 'locked hand' handle is inspired by the idea of having the hand locked in place and there by lower the strength, needed to grab around the handle.

Finger holes

The 'finger hole' handle is just another design with the same idea as the 'locked hand' handle difference is that each finger has its own hole.



Wing shaped

Inspired by the new popular mountain bike handle. Designed from a scan of the user's grip, which marks of the fingers, and a pad to rest the palm on.

Scan grip

Like the 'Wing shaped' handle the 'Scan grip' is designed to achieve the perfect diameter for every finger. Making sure the particular handle is only fits a specific individual for obtaining better results.

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Appendix C

The tables below shows results from a Two-way ANOVA with repeated measures analyse of mean and median frequency for both relative and absolute measurement. There are no significant difference between means.

Absolut mean freq				
Anova test of within subjects	df	Error df	F	Sig.
Direction	1	7	0.609	0.461
Muscles	1	7	0.685	0.685
Direction*Muscle	1	7	0.229	0.229

Sd

Absolut median freq				
Anova test of within subjects	df	Error df	F	Sig.
Direction	1	7	0.591	0.467
Muscles	1	7	0.027	0.875
Direction*Muscle	1	7	0.641	0.641

Sd

relative mean freq				
Anova test of within subjects	df	Error df	F	Sig.
Direction	1	7	0.928	0.368
Muscles	1	7	1.156	0.318
Direction*Muscle	1	7	0.366	0.564

Ds

relative median freq				
Anova test of within subjects	df	Error df	F	Sig.
Direction	1	7	1.193	0.311
Muscles	1	7	0.224	0.650
Direction*Muscle	1	7	0.661	0.443

Absolut RMS				
Anova test of within subjects	df	Error df	F	Sig.
Direction	1	7	0.122	0.737
Muscles	1	7	2.305	0.173
Direction*Muscle	1	7	0.108	0.752

relative RMS				
Anova test of within subjects	df	Error df	F	Sig.
Direction	1	7	1.692	0.235
Muscles	1	7	1.484	0.263
Direction*Muscle	1	7	2.126	0.188