2014•2015
FACULTEIT GENEESKUNDE EN LEVENSWETENSCHAPPEN
master in de revalidatiewetenschappen en de kinesitherapie

Masterproef

What is the effect of a 4 week training program on force enhancement?

Promotor :
dr. Pieter VAN NOTEN

Jens Adams , Michael Van Grieken
Scriptie ingediend tot het behalen van de graad van master in de revalidatiewetenschappen en de kinesitherapie

Universiteit Hasselt | Campus Hasselt | Martelarenlaan 42 | BE-3500 Hasselt
Universiteit Hasselt | Campus Diepenbeek | Agoralaan Gebouw D | BE-3590 Diepenbeek

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KNOWLEDGE IN ACTION

1. PREFACE

Our gratitude goes to Dr. Pieter Van Noten, our promoter, who led us through the aspects of scientific research. We appreciate his help in designing and carrying out the study as well as processing the data.

Our colleagues Wouter Robijns, Yorben Hons, Ben Janssen and Jens Vleugels who worked with us on this study. Also the colleagues from master 1 who assisted in the acquisition of the data are to be thanked for their contribution to this study.

Furthermore we would like to thank the participants, who helped us to acquire the data we needed by being willing to make time for our research as well as their effort to participate in the training programs. Without these people the study would have never come to this.

Finally our gratitude goes to UHasselt. She gave us the opportunity to be part of a research on a scientific level, especially by letting us use the Biodex and fitness area in the REVAL-facilities.

Hasselt, June 10 2015

Jens Adams & Michael Van Grieken

Michael Van Grieken	Jens Adams
Ogentrooststraat 1	Bergenstraat 6
2200 Herentals	2322 Minderhout
België, 22/06/2015	België, 22/06/2015

2. BACKGROUND

This thesis is written from a physiotherapy point of view. It is an essential component of getting a Master Degree in physiotherapy and rehabilitation sciences at University Hasselt. This article is the second part of our thesis, it is a continuation of thesis 1 (Adams, Van Grieken, 2014). We hereby directly address the scientific world, more specifically physiotherapy, rehabilitation sciences, skeletal muscle physiology and skeletal muscle biomechanics.

We know from our research in thesis 1 that the phenomenon 'force enhancement' is not quite known, not even by health-care or training professionals. Force enhancement is the phenomenon where an eccentric phase has an influence on the following isometric phase, all within one muscle contraction. In this case: the influence is expressed as a higher amount of force delivered by that muscle. The exact mechanism of this phenomenon is not yet known. There are a few theories on different aspects of force enhancement that are more or less accepted, however there is no consensus on what the precise mechanism is that entirely explains this force enhancement. In this study we focus on force enhancement. By using the basis that was thesis 1 (getting to know force enhancement and its possible mechanisms and the training modalities for eccentric training), we have a fitting framework to do this study.

This is a pilot-study under the guide of Dr. Van Noten. He is trying to get insights in training-studies about force enhancement. Six students: Jens Adams, Michael Van Grieken, Wouter Robijns, Yorben Hons, Ben Janssens and Jens Vleugels under the guide of Dr. Van Noten designed this study. All of the aspects and agreements were made by team discussion. Recruitment, data-acquisition, processing and interpreting is therefore done by every member of this team. The data of this study is used by these six students in order to get an answer to the research questions each student (or pair of students) has put out.

This study fits in the world of physiotherapy and rehabilitation sciences because force enhancement is used by the human body in every day movements. We tried to investigate the effect of a period of training on the force enhancement of a skeletal muscle. This has never been studied before and there is no relevant literature available that acts on this subject. We hope to contribute to the scientific world, especially physiotherapy and its research for force enhancement.

3. Abstract

Background: The phenomenon 'force enhancement' has been observed in studies. No consensus about the mechanisms has been reached so far. Most studies are performed in vitro on myofibrils or sarcomeres. Very few studies were performed on humans in vivo. If an eccentric phase has an influence on a following isometric phase, we want to investigate if training has an effect on force enhancement. The effect of training on force enhancement has never been studied before.
Methods: The aim of this study was to research the effect of a 4 week training program on isometric muscle strength and eccentric muscle strength. We also wanted to evaluate if force enhancement occurred in large muscle groups. Finally we wanted to evaluate the effect of this training program on the trainability of force enhancement. This pilot study recruited 21 male subjects, aged between 18-30 years. Participants were measured before (pre-test) and after the training program (post-test). Measurements were performed using the Biodex isokinetic dynamometer.
Results: The training program resulted in a significant improvement in muscle strength during a purely isometric contraction, an isometric contraction following an eccentric contraction with a speed of 30°/s and an isometric contraction following an eccentric contraction with a speed of 60°/s are observed. Force enhancement was not observed during the contractions.
Conclusion: Muscle strength improved in all contractions after the 4 week training program. No force enhancement was observed during the study for the pre-test and the post-test. No statement is made about the trainability of force enhancement. Further in vivo studies are recommended.

Keywords: skeletal muscle, force enhancement, eccentric training, muscle strength, maximal voluntary contraction, history of muscle action

4. INTRODUCTION

Skeletal muscles can produce force in three different ways: an isometric, a concentric or an eccentric contraction. During an isometric contraction, the skeletal muscle produces a force without an increase or decrease in muscle length. During an eccentric or concentric contraction, the skeletal muscle produces respectively a force with an increase or decrease in muscle length. When an eccentric phase prior to an isometric phase is performed during the same muscle contraction, a phenomenon called 'force enhancement' occurs. Force enhancement is defined as the increase in the steady-state isometric force following a stretch compared to the purely isometric force at the corresponding length (Herzog, 2002).

Force enhancement can be divided into two components (Rassier, 2012; Rassier and Herzog, 2002). The first component, called 'force enhancement during stretch', can be explained by the cross-bridges model. An increased number of attached cross-bridges and an increased strain of these cross-bridges during a stretch of the sarcomeres, can explain this phenomenon (Rassier and Herzog, 2002). The second component of force enhancement is called 'force enhancement after stretch' or 'residual force enhancement'. Residual force enhancement is increased force, which occurs after the eccentric stretch phase of the muscle contraction. When the isometric phase is reached, the force reaches a steady-state. This steady state occurs when the force values remains more or less stable. Residual force enhancement can be subdivided into an active component and a passive component. The exact explanations of the working mechanisms are unknown and no consensus has been reached about the underlying mechanisms. Further investigation is necessary to reach a consensus about the exact mechanisms.

In vivo, not all people will respond with an increase of isometric force after an active eccentric phase. There will be responders and non-responders (Seiberl et al., 2015). Thus, only a subset of subjects respond to active lengthening by residual force enhancement while others do not (Seibert et al., 2015). In contractions of the musculus quadriceps femoris, only 70-80 % responded by residual force enhancement (Seiberl et al., 2012). A study by Oskouei and Herzog (2005) on the musculus adductor pollicis showed only 47% of the subjects responded by residual force enhancement. These studies showed that it is more difficult to provoke residual force enhancement in vivo.

Eccentric strength training has shown to be effective in improving isometric strength (Kaminski et al., 2009; Paddon Jones et al., 2001; Krentz et al., 2010). This improving in strength can be associated with adaptations of the neuromuscular system, an increase in the proportion and cross-sectional area of type 2 muscle fibers and possibly, an alteration of the muscle architecture (Isner-Horobeti et al., 2013). If these alterations of muscle architecture after an eccentric training period have an influence on the amount of force enhancement, it would be trainable. Lindstedt et al. (2002) investigated the hypothesis of muscle/tendon stiffness plasticity after an eccentric training program in stretch-shortening contractions and demonstrated a significant increase in muscle spring stiffness. Following eccentric training, all the subjects performed a higher countermovement jump than they did prior to training, while the subjects of the control group (traditional concentric exercises) did not improve (Lindstedt et al., 2002). Muscles and tendons are capable to store elastic energy during an eccentric phase and release this elastic energy during a concentric phase, which is an explanation of the higher jumping capacities in the stretch-shortening cycle. Lindstedt et al. (2002) suggested that the crucial element of the muscle spring stiffness in stretch-shortening contractions is the titin protein. The stiffness of titin depends on its environment and would be influenced by the amount of Ca^{2+} -ions (Labeit et al., 2003). The role of Ca^{2+} -ions could have an effect on force enhancement by influencing the stiffness of titin or the titin-actine interaction (Rassier, 2012). If titin contributes to an improvement of the countermovement jump height after an eccentric training program and titin plays a role in force enhancement, an eccentric training program could increase the amount of force enhancement. In the past, no studies were conducted about the trainability of force enhancement.

In this study, we want to research if force enhancement can be provoked during the pre-test and during the post-test after the 4 week training program. Therefore it is important to investigate the difference between the pre-test and the post-test, so we can research the effect of training on the amount of force enhancement. If there is a training effect, the amount of force enhancement during the post-test will be greater than the amount of force enhancement during the pre-test.

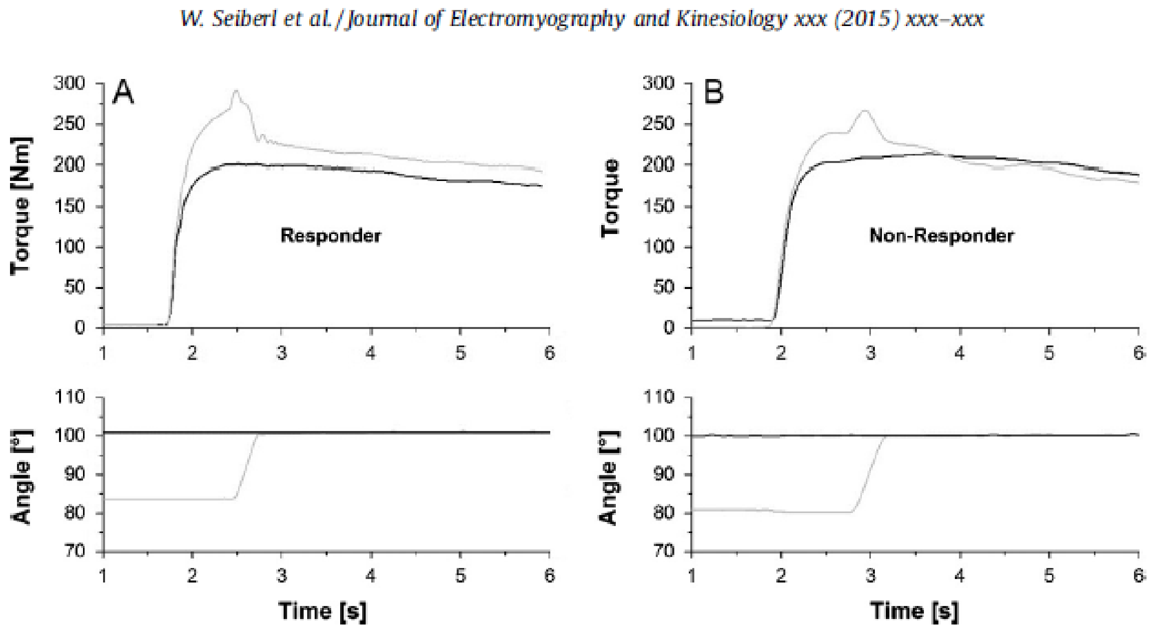


Fig. 1 (Seiberl et al., 2015) shows the typical lengthening contraction in gray and the typical reference isometric contraction in black. In responders, the difference between the grey and the black line is significant during the isometric phase. That way you can conclude that residual force enhancement occurs. In non-responders, there is no difference between the grey and black line during the isometric contraction. In that case, you cannot speak of residual force enhancement.

5. METHODS

The study was carried out on 18 male Belgians by master students of the University of Hasselt. The measurements were performed at REVAL Hasselt. All participants were informed in detail about the training and the study. The study was approved by the ethical commission of University Hospitals of the KULeuven and University of Hasselt. Our research questions were: (1) is there fatigue during the test protocol? (2) Is there a significant improvement of the isometric contractions between pre -and post measurements? (3) Does the phenomenon ‘force enhancement’ happen during the pre-test and the post-test? (4) If the phenomenon happens, is force enhancement trainable after a 4 week program?

PARTICIPANTS

Male adults aged between 18 and 30 years, with no recent injuries to the non-dominant leg, responded were and included to participate in our study. Female participants and participants with recent injury to the non-dominant leg were not included. The participants were invited by social networking by the performers of this study. 21 men responded and were included in this study. During the 4 week training program, 3 men dropped out. Two of the drop-outs were due to lack of time to train and one of them could not finish the program due to pain in the hamstring area.

EXPERIMENT

Each subject needed to follow a 4 week training program. This training program consisted of 2 components: a series of body-weight exercises and a series of exercises on machines. To measure the improvements we installed a pre-test and a post-test. They are guided by one of the authors or one of the examiners (background). These ‘personal coaches’ tried to motivate and help them during these 4 weeks, to get optimal results. They contacted the subjects on a regular basis and guided them once a week in the training facility. The subjects were tested before and after the training program. The training program was based on the movement of the knee extension, which is mainly performed by the contraction of the musculus quadriceps. In this study we will only analyze the data from the knee movements.

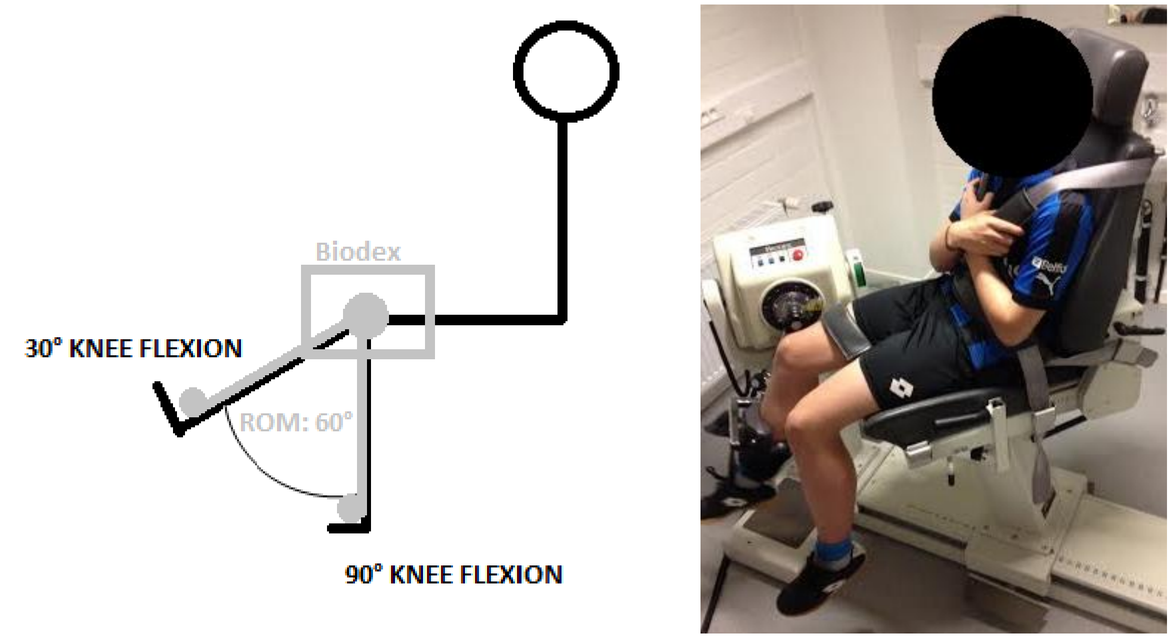
Pre-test	Training program 4 weeks	Post-test
Isometric contraction 1		Isometric contraction 1
Reactive contractions: 30°/s and 60°/s		Reactive contractions: 30°/s and 60°/s
Isometric contraction 2		Isometric contraction 2

Measurements

The Torque production (Nm) of each subject is measured by a series of tests on an isokinetic dynamometer (Biodex). These tests were taken before the 4 week training program and after the 4 week training program. Each subject was seated on the BioDex chair and placed in such a way that the biomechanics were respected. For the Quadriceps muscle a range of motion (ROM) of 60° was installed. The movement was stopped at 90° knee flexion. This is what we called the reference length in this study. So we used a range of motion between 90° knee flexion and 30° knee flexion (fig. 2). This measurement consists of 4 components for the Quadriceps:

1. **Isometric 1 contraction**: The lever of the Biodex is stationary on the reference length. The subject pushes maximally against the arm by performing a leg extension. This contraction is repeated three times for a period of 8 seconds with 90 seconds rest in between the contractions.
2. **Reactive contractions**: The lever of the Biodex starts at 30° knee flexion. There the subject needed to resist the torque produced by the lever arm three times with a speed of 30°/s and three times with a speed of 60°/s, to the reference length. The subject needed to push maximally against this resistance. The speed of the lever was constant. In this phase the subject performs a maximally voluntary eccentric contraction. When the lever is stationary at the reference length, we asked the subject to keep pushing for 8 seconds, so we could record the isometric phase that followed. 90 seconds rest between the contractions was used for rest interval. Six contractions in total, three with a speed of 30°/s and three with a speed of 60°/s were performed.
3. **Isometric 2 contraction:** This is an exact repetition of the first isometric contraction. We used this measurement to evaluate if fatigue occurred during the test protocol.

Fig. 2: set-up of the measurements



Training program

First, once a week a subject had to train at REVAL or in a fitness area, where he needed to perform a series of exercises on machines. This was a very analytical performance of these muscles. On this training day, they had to do the home exercises as well, so the personal coach could correct them if the exercises were not performed correctly.
Second, twice a week they had to perform a series of body weight exercises at home. A subject trained three times a week in total.

<u>Fitness exercises</u>

The training program in Reval or other training facilities consisted of two fitness exercises. These exercises and their training volume (table 3) are described below:

1. Leg Press: 2 legs concentric contraction, eccentric contraction in the non-dominant leg.
2. Leg Extension: 2 legs concentric contraction, eccentric contraction in the non-dominant leg.

Table 3: training volume Reval/training facilities (1x/week)

	Week 1	Week 2	Week 3	Week 4
Leg press	80% 1RM 3 sets 8 repetitions	80% 1RM 3 sets 12 repetitions	100% 1RM 3 sets 8 repetitions	100% 1RM 3 sets 12 repetitions
Leg extension	70% 1RM 3 sets 8 repetitions	70% 1RM 3 sets 12 repetitions	90% 1RM 3 sets 8 repetitions	90% 1RM 3 sets 12 repetitions

<u>Home-exercises</u>

This training program has to be performed 2 times at home and 1 time in the training facility or at Reval. These exercises and training volume (table 4) are described below:

1. Unipodal Squat: 1 leg eccentric, 2 legs concentric
2. Lunge with the non-dominant leg in front

Table 4: training volume home exercises (3x/week)

	Week 1	Week 2	Week 3	Week 4
Unipodal squat	squat to 90° 3 sets 8 repetitions	squat to 90° 3 sets 12 repetitions	squat until other knee nearly touches the floor 3 sets 8 repetitions	squat until other knee nearly touches the floor 3 sets 12 repetitions
Lunges	lunge, foot on the floor 3 sets 8 repetitions	lunge, foot on the floor 3 sets 12 repetitions	lunge, foot on step 3 sets 8 repetitions	lunge, foot on step 3 sets 12 repetitions

6. DATA-ANALYSIS

The Biodex system measured all torque-values with an interval of 10ms during the performances of the subjects. Biodex uses his own analysis program, however no analysis program is included for the measurement of force enhancement. Therefore we had to write our own analysis program. We calculated the mean of the torque-values between 5-6 seconds of the contraction from the reactive contraction and the isometric contraction. First we performed a paired t-test on the mean values of the first isometric contraction and the last isometric contraction within one protocol to evaluate fatigue. A paired t-test was used to measure the difference between the first isometric contraction and the reactive contractions, also in one test protocol. These values were used to interpret the absolute force enhancement. The tests were performed for the pre-test and the post-test. Secondly, we evaluated the effects of training on the different contractions by performing a paired t-test on the mean values of the first isometric contractions and both of the eccentric contractions from the pre-test and the post-test. Both speeds, 30°/s and 60°/s, were used for the reactive contraction set-up. To calculate the absolute force enhancement, we used the difference between the reactive data and the isometric 1 contraction. We only used isometric 2 contraction to analyze if there is fatigue during the measurements.

Statistical analyses were performed using the JMP statistical discovery software from SAS for Windows. A p-value less or equal to 0,05 was accepted to statistically significant.

7. RESULTS

IS THERE FATIGUE DURING THE MEASUREMENTS?

Before the reactive measurements started, each subject had to perform a maximal isometric contraction. At the end of the measurement, a second isometric contraction was performed by the subjects. This second isometric contraction was used to evaluate the fatigue during the measurements. Results of the data-analyses between this two isometric contractions showed no significant difference (pre-test: p=0,15; post-test: p=0,08).

IS THERE A SIGNIFICANT IMPROVEMENT OF THE ISOMETRIC CONTRACTION AND THE REACTIVE CONTRACTIONS BETWEEN PRE -AND POST MEASUREMENTS?

As shown in figure 3 and 4, the strength of the purely isometric contractions during the post-test were significant improved by 9% in comparison with the purely isometric contractions during the pre-test (p=0,04). The strength measured during the reactive contractions also improved significant after the training program for both speeds. The isometric strength following the eccentric contraction of 30°/s improved by 8% (p=0,02). The isometric strength following the eccentric contraction of 60°/s improved by 6% (p=0,04).

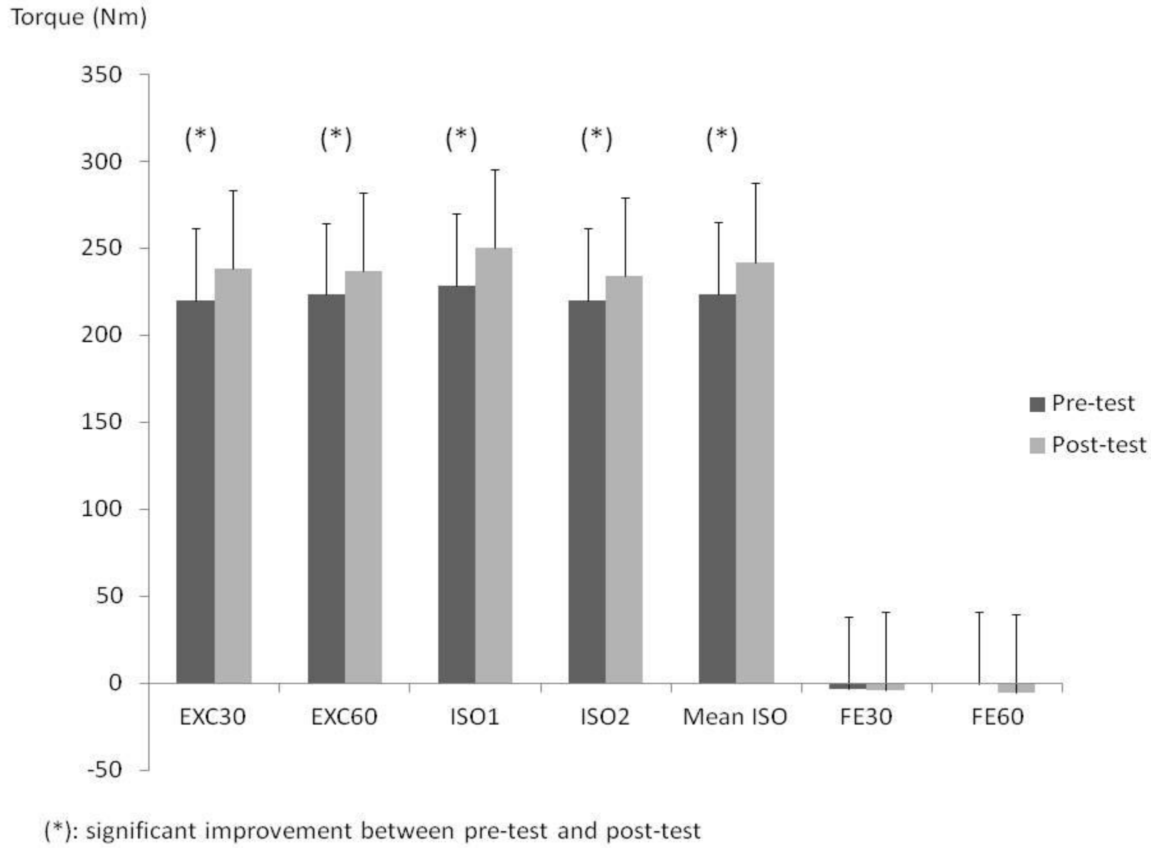


Fig 3: Mean torque values and standard deviations for the contractions during the pre-test (dark grey) and post-test (light gray) with EXC30 (reactive contraction with a speed of 30°/S), EXC60 (reactive contraction with a speed of 30°/s), ISO1 (isometric contraction 1), ISO2 (isometric contraction 2), Mean ISO (mean values of isometric contraction 1 and 2), FE 30 (force enhancement with a speed of 30°/s) and FE60 (force enhancement with a speed of 60°/s).

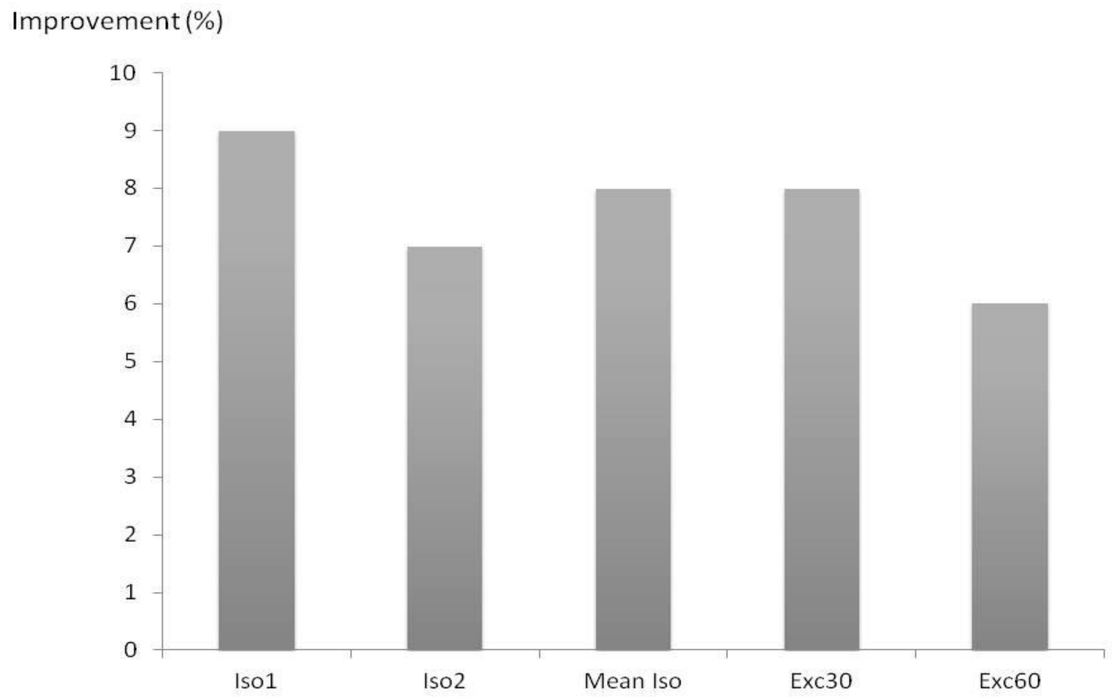


Fig 4: Percentage of improvement between pre-test and post-test with EXC30 (reactive contraction with a speed of 30°/S), EXC60 (reactive contraction with a speed of 30°/s), ISO1 (isometric contraction 1), ISO2 (isometric contraction 2) and Mean ISO (mean values of isometric contraction 1 and 2).

DOES THE PHENOMENON 'FORCE ENHANCEMENT' HAPPEN DURING THE PRE-TEST AND THE POST-TEST?

In all situations, there is no force enhancement measured in the pre-test and the post-test. During the pre-test , no force enhancement is observed during the 30°/s trials (p=0,94) and during the 60°/s trials (p=0,75). During the post-test, no force enhancement is observed during the 30°/s trials (p=0,87) and during the 60°/s trials (p=0,86).

IF THE PHENOMENON HAPPENS, IS FORCE ENHANCEMENT TRAINABLE AFTER A 4 WEEK PROGRAM?

The phenomenon of force enhancement did not occur during the tests. Because it doesn't happen, we cannot evaluate the trainability of force enhancement in this setting.

8. Discussion

The absence of force enhancement

A lot of studies showed the existence of the phenomenon 'force enhancement'. The biggest purpose of this study was to research force enhancement in vivo and the trainability of force enhancement. In contrast to other studies (Lee and Herzog, 2002; Hahn et al., 2007; Power et al., 2012), the results of this study didn't show the occurrence of force enhancement during the tests. There are some possible causes for the absence of force enhancement. First, we care about the difference of in vitro studies and in vivo studies. In vitro studies were mostly performed in a controlled environment on isolated myofibrils or sarcomeres. These reduced muscle preparations were fired by involuntary electric impulses. The occurrence of residual force enhancement would be influenced by the manner of contraction. Electrically stimulated muscles in vivo would react in a different way as voluntary stimulated muscles, which can be influenced by neural control in terms of more efficient activation, increased excitability, saving of metabolic energy and altered neuromuscular states like fatigue (Seiberl et al., 2015). Some speculations are the influence of non-contractile tissue like fascia.

The second possible reason for the absence of force enhancement is the influence of age. Subjects in this study were aged between 18 – 30 years. Residual force enhancement was 2,5 times greater in older adults (mean age: 77 years) compared to young adults (mean age: 26 years) during the steady state isometric contraction phase following stretch (Power et al., 2012).

A third possible reason would be the percentage of responders and non-responders in this study. Some subjects will respond with force enhancement and some subject will not respond on a lengthening contraction (Oskouei and Herzog, 2005; Hahn et al., 2007). Despite similar absolute isometric force levels compared to non-responders, responders showed higher post-activation potential and smaller resistance to fatigue (Oskouei and Herzog, 2005). Some studies (Hahn et al., 2008; Ramsey et al., 2010) suggest that muscles with a higher amount of fast-twitch fibers show a higher amount of force enhancement.

Effect of the training program

The training program was a combination of eccentric exercises and body-weight exercises. Eccentric strength training can be effective in improving isometric, eccentric and concentric muscle strength, cross-sectional area and muscle hypertrophy (Kaminski et al., 2009; Krentz et al., 2010). Like previous studies suggested, the results showed a significant improvement in isometric strength. The isometric strength following an eccentric contraction with a speed of 30°/s and 60°/s also improved after the training program. In this study, we advised the subject to perform the exercises with an explosive, high speed. We suggest that the velocity of contraction and the velocity of contraction during the training program could have an influence on the amount of isometric strength. Paddon Jones et al (2001) showed a significant difference in improving muscle strength, in advantage of explosive, high-speed contractions during training programs.

MEASUREMENT OF FORCE ENHANCEMENT

The purpose of this study was to measure the steady-state residual force enhancement. We preferred to use the mean torque values 5-6s after the initiation of the contraction. The absence of force enhancement in this study, could be influenced by the used time-interval. According to the graphs used in the literature, the amount of force enhancement is bigger in the beginning of the isometric contraction (fig 5: time interval 1) after the lengthening contraction. The amount of force enhancement measured between time interval 2 is smaller (fig 5: time interval 2). Because we started the reactive contraction directly with the eccentric phase, our data is measured between 4-5s of the isometric phase during the 60°/s test and between 3-4s of the isometric phase during the 30°/s test. We used these intervals because at 60°/s the eccentric phase only lasted for 1 second while the eccentric phase at 30°/s lasted for 2 seconds. We can speculate that these time-intervals are too far to the right on the torque-time graph to measure force enhancement.

Other studies (Power et al., 2012; Hahn et al., 2007), which measured force enhancement in vivo, used a ‘quick release’ contraction. The subjects had to perform an isometric phase before the eccentric phase, so the muscle had the time to develop its maximal strength. This technique is used to avoid the time deficit zone of a muscle. In our study, the reactive contraction started directly with the eccentric phase. This could influence the torque values of the initiation of the eccentric phase and have effects on the amount of force enhancement.

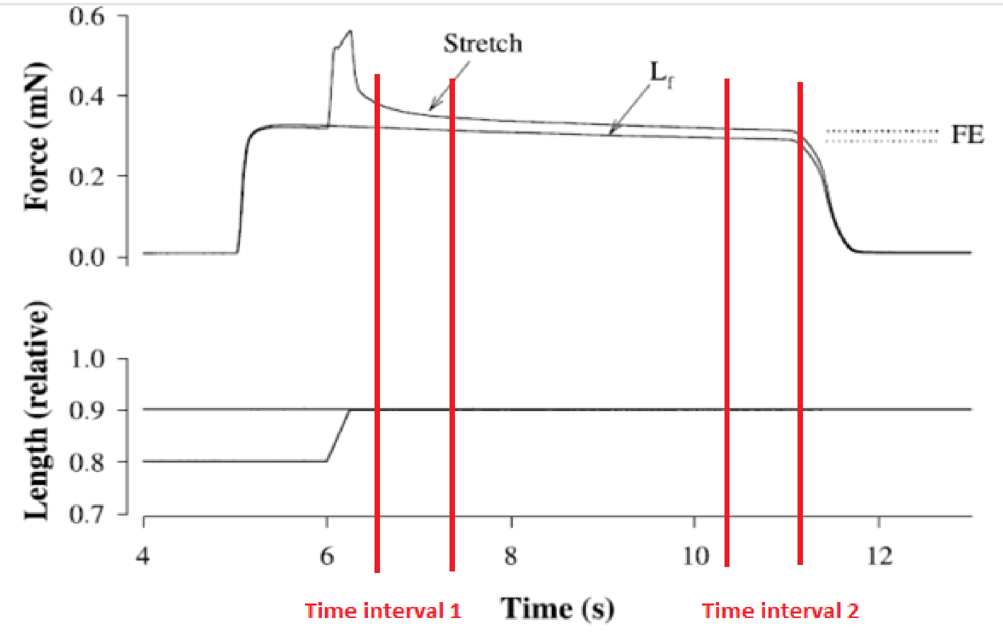


Fig 5: Force enhancement (Rassier and Herzog, 2004): the amount of force enhancement during time

interval 1 is greater than the amount of force enhancement during time interval 2.

ABNORMAL CONTRACTION CURVES

In literature, the generalized curve of force enhancement is represented as a stable line which reaches a peak directly after the end of the eccentric phase. After the eccentric phase, the graph lowers until it reaches a stable phase, called ‘steady-state’ (fig 6). In this steady-state phase, we tried to measure force enhancement. This representation of force enhancement is very theoretical. As seen in figure 7, our results showed a different kind of curve, which is not stable and varies a lot. As the torque values weren’t constant between 5-6 seconds, no steady –state phase occurred.

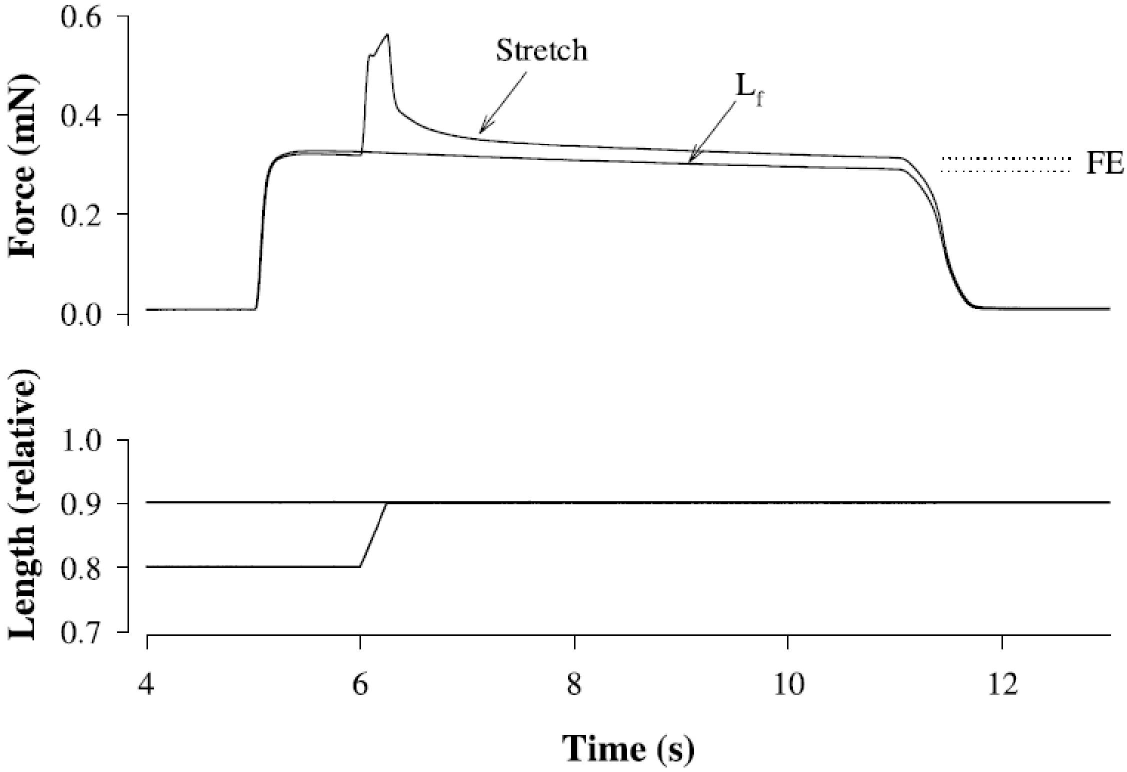


Fig 6: Force enhancement (Rassier and Herzog, 2004): simplified representation of force enhancement by in vitro studies.

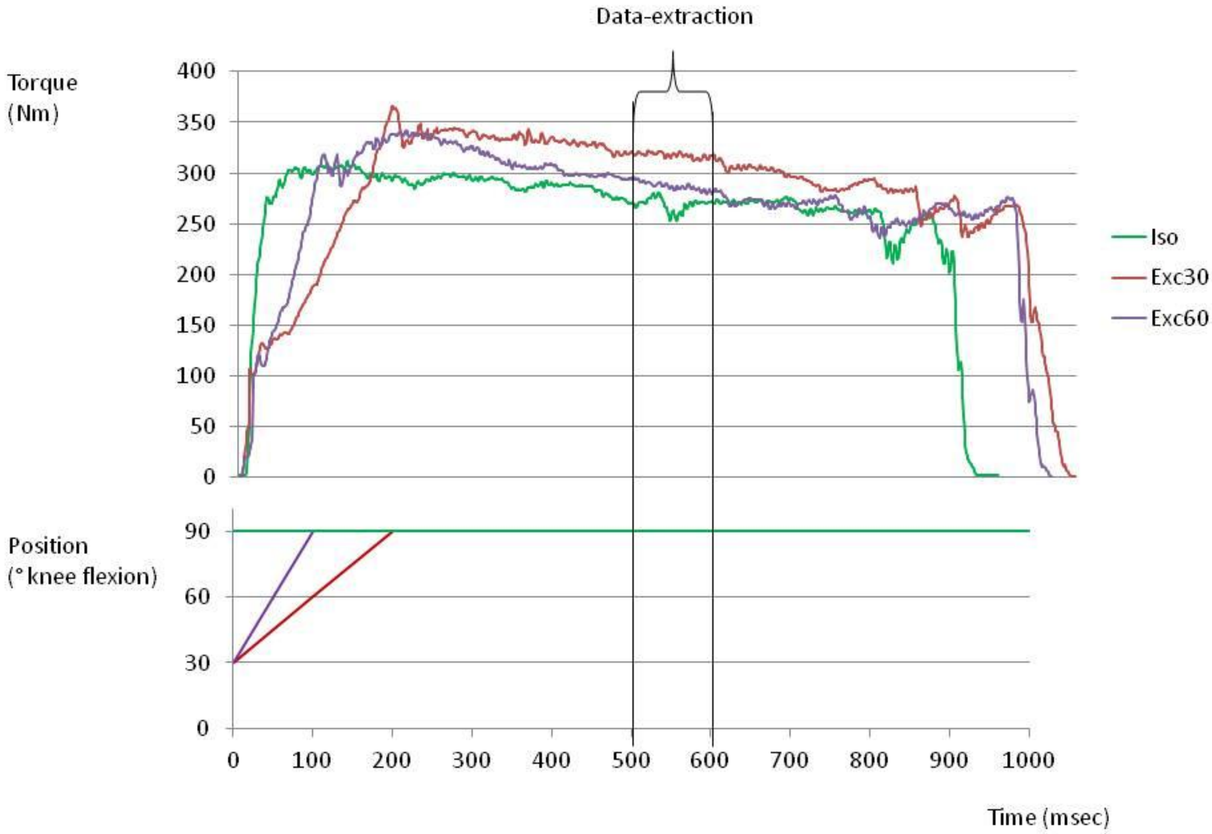


Fig 7: Raw data of 3 contraction types, performed by a subject of this study: the purely isometric contraction (Iso), the reactive contraction with a speed of 30°/s (Exc30) and the reactive contraction with a speed of 60°/s (Exc60).

9. CONCLUSION

We conclude that this 4 week training program is effective for improving isometric strength and isometric strength following an eccentric contraction for 30°/s and 60°/s. No fatigue was measured during the measurements. Although research demonstrated that force enhancement can occur within contractions we used in this study, our results suggest that there was no force enhancement during the lengthening contractions. Because the lack of force enhancement, we cannot make a statement about the trainability of force enhancement. We recommend further in vivo studies about force enhancement and the trainability of force enhancement.

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