Muscle fatigue index: reference values in typically developing children and adolescents

by

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Research context

Common motor disorders in children and adolescents are cerebral palsy (CP) [1] and neuromuscular disorders (NMD) [2]. Children and adolescents with these disorders can have upper limb weakness, which impacts activities of daily life dramatically. For example their ability to sustain grip strength is weak and this is crucial for certain skills of daily life. To investigate the ability to sustain a contraction, muscle fatigue can be measured [3]. Muscle fatigue can be described as "an exercise-induced reduction in the ability of muscles to produce force, despite the task may or may not be sustained [3]." However, muscle fatigue during grip tasks in children and adolescents with CP or NMD remains unexplored. To investigate the occurrence and severity of muscle fatigue during grip tasks in pediatric populations, reference values in typically developing children (TD) are required. Therefore, the aim of this study was to obtain reference values of muscle fatigue in grip and pinch strength in typically developing children and adolescents and to investigate if factors such as maximal strength, age, gender, physical activity, body weight and height have an influence on muscle fatigue.

This experiment is situated in the research field of pediatric rehabilitation and is closely related to neurologic rehabilitation. This study fits the research line of Prof. K. Klingels on upper limb function in children with unilateral CP as well as in the broader framework of the PhD project of Dra. D. Severijns, entitled "Motor fatigability of the upper limb in Multiple Sclerosis." Furthermore, this thesis is a continuation of the master thesis of Kendra de Koninck, entitled ''Muscle fatigue during isometric grip tasks in adolescents with unilateral cerebral palsy."

The design of this experiment was drafted by the students in collaboration with Prof. K. Klingels, Dra. D. Severijns and Dr. E. Rameckers of the Rehabilitation Centre 'Adelante' in Hoensbroek. Typically developing children and adolescents between seven and 16 years old were recruited in different schools and youth movements in Belgium and examined by the students.

The experimental data was processed with a custom-made program written by Dra. Severijns. Thereafter the students performed the statistical analysis and wrote this master thesis. Prof. K. Klingels and Dra. D. Severijns performed the proofreading.

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Muscle fatigue index: reference values for typically developing children and adolescents

AIM: To obtain reference values of muscle fatigue in grip and pinch strength in typically developing children and adolescents, to enable an adequate comparison with children and adolescents with motor disorders. Determine the influence of actors such as maximal strength, age, gender, physical activity, body weight and height on muscle fatigue.

METHOD: In 118 typically developing children and adolescents between seven and 16 years old, maximal strength and muscle fatigue during a 30 seconds maximal isometric contraction were measured in both hands in two conditions: hand grip and pinch grip. Muscle fatigue was calculated with the static fatigue index (SFI). Anthropometric variables including weight, height, upper and lower arm and hand length were assessed. A questionnaire on the amount of extracurricular physical activity was filled in.

RESULTS For both grips and both hands, the maximal strength increased significantly with age. Interaction between age and gender was found in maximal strength, more specifically in the age group of 15-16 years, boys were significantly stronger than girls ($p=0.003$). The dominant hand and pinch grip was significantly stronger than the non-dominant grips in all ages ($p<0.0001$). A significant decrease in SFI was found among the age groups, except for the dominant hand grip. The SFI for the non-dominant grips were higher than the dominant grips (p= <0.001-0.02). High positive correlations were found between maximal strength and anthropometric variables and physical activity (r=0.74 – 0.90). For SFI, low to moderate negative correlations were found with maximal strength, upper and lower arm length and hand length (r=-0.17 – -0.41).

INTERPRETATION Provisional reference values of muscle fatigue in the upper limbs of typically developing children and adolescents are provided. SFI decreased with increased age, the dominant hand showed less muscle fatigue than the non-dominant hand and SFI of the pinch grip was higher than SFI of the hand grip. Anthropometric variables had little to fair influence on muscle fatigue.

What this paper adds:

- SFI decreases with increasing age.
- The dominant hand shows less muscle fatigue compared to the non-dominant hand.
- SFI of the pinch grip is higher than SFI of the hand grip.

INTRODUCTION

Common motor disorders in children and adolescents are cerebral palsy (CP) [1] and neuromuscular disorders (NMD) [2]. CP is a group of disorders of the movement and posture caused by non-progressive disturbances in the developing fetal or infant brain [4]. Motor impairments in children with CP include abnormal muscle tone, muscle weakness and coordination problems [4]. Grip strength is often impaired in children and adolescents with CP. A study of Klingels et al. (2011), showed that the mean relative grip strength of the affected side in children with unilateral CP was 40 % compared to the non-affected side [5]. Furthermore, a high correlation between grip strength and bimanual performance and daily activities was found (r_s =0.75-0.76) [5].

Where CP is a movement disorder, caused by the central nervous system, NMD is an umbrella term describing hereditary or acquired clinical syndromes affecting elements of the nervous system, as neuromuscular junction, peripheral nerves and muscles. Motor weakness is a present symptom of all NMD, such as Duchenne muscular dystrophy (DMD), hereditary motor and sensory neuropathy (HMSN), spina bifida myelomeningocele (SBM) and spinal muscular atrophy (SMA) [6]. A study of Seferian et al. (2015) showed that in boys with DMD upper limb weakness manifests when the boys are still ambulant and gradually increases from the proximal to the distal muscles [7]. In the end stage, movements are limited to the fingers. Furthermore, HMSN, also known as Charcot-Marie-Tooth disease (CMT), is characterized by progressive muscle weakness and wasting and by sensory loss. The intrinsic muscles of the hands are primarily affected in the upper limb, manifested by clawing and impaired hand function [8]. The study of Videler et al. (2008) showed that this can lead to impaired manual dexterity and that activities that require finger grips are most limited [9]. Upper limb function is also limited in the majority of children with SBM [10]. Hand function is impaired in the performance of everyday tasks like opening a jar, turning pages, objects, simulating eating, writing, and card lifting [11]. Moreover the study of Deymeer et al. (2008) showed that in children with spinal SMA type IIIb show a gradual but clear decline of muscle strength with age. In some patients the strength of the triceps was already weak at two years and at 15 years most patients had moderate to severe weakness. At the age of five years the biceps and deltoid started getting weak and at ten years, the biceps showed a mild weakness, while the deltoid showed a slower decline [12].

As shown above, the maximal strength of the upper limbs is important in daily life in children with motor disorders. Besides maximal strength in the upper limbs, the ability to sustain a contraction for longer periods, defined as muscle endurance, is also important. This is even required in simple activities in daily life, for example for drinking a cup of tea, an amount of force is needed to pick up the cup, but the contraction must be sustained, to be able to drink from it. Other examples are carrying a box, brushing teeth, writing, eating or playing with toys. To investigate the ability to sustain a contraction, muscle fatigue can be measured [3]. Muscle fatigue can be described as "an exercise-induced reduction in the ability of muscles to produce force, despite the task may or may not be sustained" [3] and is referred to as fatigue during motor tasks, but it is not the point of task failure or when the muscles become exhausted [13]. Several assessment methods for muscle fatigue have already been documented in literature, but the most commonly used measurement techniques are surface electromyography (sEMG) or muscle fatigue indices based on strength measurements [14-16]. Surface EMG can be used to monitor local muscle fatigue as it indicates the physiological and biochemical changes in skeletal muscles during a fatigue protocol. Muscle fatigue is demonstrated when there is an increase in amplitude and a shift towards lower frequencies [14]. Secondly, muscle fatigue may be calculated with indices, based on strength measurements of either repetitive or sustained contractions. During a sustained contraction, the static fatigue index (SFI) is calculated as a ratio between the actual measured area under the time-strength curve and the hypothetical area under the curve if no strength loss would occur. Former studies already used this index to determine muscle fatigue in CP and multiple sclerosis (MS) [15, 16].

As a first step towards understanding muscle fatigue in pathological paediatric populations, more insights of muscle fatigue in typically developing children and adolescents are required. So far, only a few studies have been published on muscle fatigue in typically developing children and adolescents, focusing only on the lower limbs [17-21]. One of these studies investigated the effect of plyometric training on muscle fatigue in 23 boys with an age of ten years [19]. During a two minute maximum voluntary contraction (MVC), a significant increase in central muscle fatigue and decrease in peripheral muscle fatigue was found. Furthermore, previous studies showed that gender does not have an influence on muscle fatigue. Christos et al. (2006) investigated muscle fatigue with EMG in 30 healthy prepubertal children, including 15 boys and 15 girls between nine and 11 years. Results showed that muscle fatigue of the medial gastrocnemius and the soleus did not differ between boys and girls. These results were confirmed for muscle fatigue, calculated by indexes, in the knee flexors and knee extensors [17, 18]. Also age has been shown to influence muscle fatigue, with more muscle fatigue in older age groups [17]. Furthermore, only one study investigated the influence of body weight on muscle fatigue. Maffiuletti et al. (2008) found no significant differences in central and peripheral muscle fatigue in the knee extensors between an experimental group of ten severely obese male adolescents between 13 and 17 years and an age-matched control group.

In conclusion, studies on muscle fatigue in TD children and adolescents are limited to the lower limbs and knowledge on influencing factors is sparse. However, as muscle fatigue in the upper limbs can hinder the performance of bimanual activities, further study in TD children as well as in children with motor disorders is warranted. The aim of this study was therefore to obtain reference values of muscle fatigue in grip and pinch strength in TD children and adolescents, to enable an adequate comparison between TD children and children and adolescents with motor disorders. Furthermore, factors such as maximal strength, age, gender, physical activity, body weight and height were investigated to determine their influence on muscle fatigue. It was hypothesized that reference values might differ for age, with a higher age showing higher values for muscle fatigue [17]. Furthermore, it was hypothesized that maximal strength and physical activity might correlate with muscle fatigue as opposed to gender, weight, height, arm length and hand length [18-21].

MATERIAL AND METHODS

Participants

TD children and adolescents aged between seven and 16 years were recruited from Flemish schools and youth movements in Belgium between October 2015 and February 2016. Children had to be able to understand and fully comply with the assessments. A questionnaire to identify health related problems was completed by the parents a few days before testing (Appendix I). Children with known chronic cardiac, respiratory, neurological or musculoskeletal disorders were excluded. For each age, a minimum of eight boys and eight girls were tested.

The study was approved by the Ethics committee of the KU Leuven (S57029) and the Medical Ethical committee of Hasselt University.

Protocol

The children were examined by two physical therapy students. First, height, weight and the length of the upper arm (from acromion to the medial epicondyle of the humerus), lower arm (from the proximal head of the radius to the radial styloid process) and length of the hand (line between distal radius and the top of the distal phalanx of the third finger) were determined on the dominant side with a tape measure and an electronic scale (Figure 1). Also, the participants and their parents were asked to complete a questionnaire of five questions, on the participation of extracurricular sport activities or physical activity (Appendix I). The questionnaire was developed based on the Godin Leisure-Time Exercise Questionnaire [22] in collaboration with KU Leuven, UHasselt and UZ Leuven. For the conversion of the physical activity to a numerical value. The weekly frequencies of the different activities were multiplied with nine for a strenuous activity, including basketball, soccer, running, and so forth. It was multiplied with five for a moderate activity, such as tennis, baseball, volleyball and multiplied with three for a light activity, including yoga, bowling, golf and so forth. The following formula was used [22]:

$$Weekly\ physical\ activity\ score = (9\ x\ Strenuous) + (5\ x\ Moderate) + (3\ x\ Light)$$

The maximal grip tests and the 30 seconds isometric endurance tasks were performed with a digital Jamar dynamometer (E-link, Biometrics Ltd, Newport, UK). Two conditions were analysed: hand grip and pinch grip (Figure 2). The grip position was adjusted to the hand size. For most children grip position two was chosen, but for the children with small hands, grip position one was chosen.

The participant was seated on a chair with his/her back straight and feet flat on the ground. The forearm was supported on the table and was positioned in a neutral position, between supination and pronation. If the child could not support his or her hand in this position, the forearm was fixated. The wrist was in a neutral position between flexion and extension.

After calibration of the digital Jamar dynamometer (E-link, biometrics Ltd, Newport, UK), the participant was asked to squeeze as hard as possible for maximal three seconds. Three repetitions with rest of 30 seconds were performed and in case there was a difference of more than 20% between the three measurements, one additional measurement was performed. The closest three results of the maximal force measurements were used to calculate the mean maximal force. First, the dominant hand was tested and thereafter the non-dominant hand.

For the isometric endurance task, a maximal contraction for 30 seconds was performed. The participant was instructed to squeeze as hard as possible. The following instructions were given: “Ready to squeeze, three, two, one and squeeze”. The participants were verbally encouraged and received visual feedback about the elapsed time during the test.

The same procedure was used for the pinch grip measures, which were performed with the biometrics’ pinch meter. The thumb of the participant was placed on the side of the sensor and the rest of the fingers at the back of the pinch meter, as shown in figure 2B.

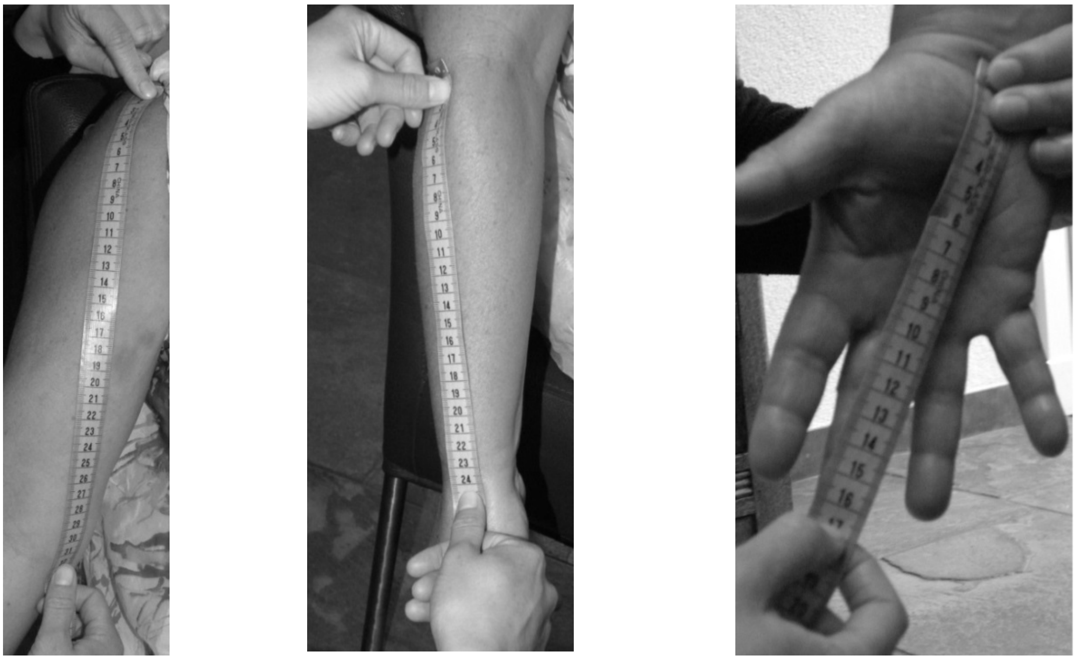


Figure 1: Left picture shows the length of the upper arm, middle picture shows the length of the lower arm, right picture shows the length the of hand

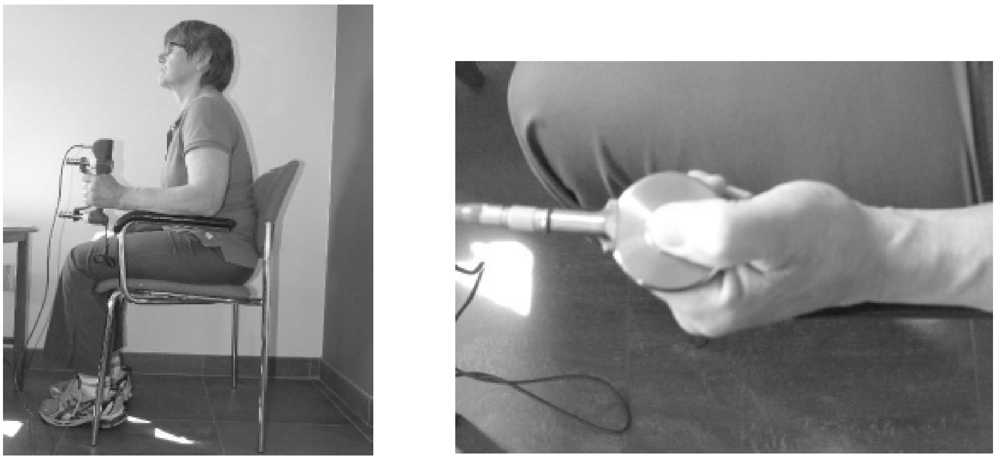


Figure 2: Left picture shows the testing positon of the hand grip without fixation of the arm, the right picture shows the pinch grip.

Primary outcomes

The muscle fatigue index is based on the assumption that the maximum force is reached in the first ten seconds and that the calculation of fatigue should start after this point. The first step was to determine the absolute peak force (kgs) and the time to peak moment (TPM) with custom-made software in labview. The second step was to determine the hypothetical area under the curve (HAUC), which is the curve when the subject would keep the force constant throughout 30 seconds, area B and C as shown in figure 3. The calculation of the actual area under the curve (AUC) was the third step and was done on the basis of the area under the force-time curve from TPM to 30 seconds, area C (Figure 3) [15, 23]. Finally, the following formula was used for calculating the fatigue index [23]:

$$100\%\ x\ (1 - \frac{AUC}{HAUC}) = 100\%\ x\ (1 - \frac{AUC_{TPM0-5-30}}{Fmax_{0-5}\ x\ (TPM_{0-5} - 30)})$$

Measurements were excluded if the TPM was not within the first five seconds, when this was not due to a measurement error or if there was a fast decrease in force observed in the first five seconds. For example, the TPM was at 5.55 seconds and this force at this point was 0.9 kg higher than the highest force within five seconds. This was not due to a measurement error, the child effectively squeezed harder and therefore this measurement was excluded. Another example of a measurement that was excluded: the TPM was at 9.95 seconds, with a force that was 0.8 kg higher than the highest force within the first five seconds. There was also a decline of 1.5 kgs at five seconds and two kgs at six seconds. This shows that the child could not sustain the force and therefore this measurement was excluded.

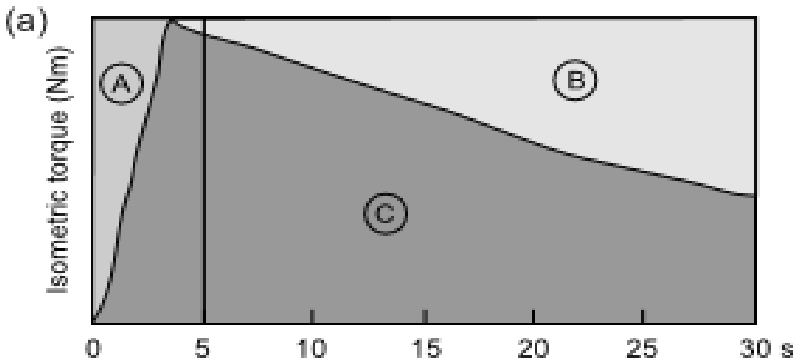


Figure 3: "Hypothetical torque (Nm) versus time (s) curve during isometric contraction sustained for 30s. (a) Fatigue index based on area under the curve for the entire contraction period of 30 s, A: TPM, B: HAUC, C: AUC [23]

Secondary outcomes

Descriptive anthropometric data of the participants, such as, gender, height, arm length, hand length and weight were collected. Age and the amount of extracurricular physical activity by the participants were obtained too.

Statistical analysis

Descriptive statistics were calculated to describe the results of muscle fatigue, maximal strength, weight, height, upper and lower arm length, and hand length with regard to the five age groups and gender in mean and standard deviations.

Five age groups were defined; 7-8 years, 9-10 years, 11-12 years, 13-14 years, 15-16 years. Physical activity scores were converted by multiplying the amount of physical activity with a factor, depending on the intensity of the physical activity [24]. Thereafter, four physical activity groups were formed based on equal distribution of participants in each group; group 1: score 0 (no extracurricular activity), group 2: score 1- 16.5 (low extracurricular activity), group 3: score 17- 40.5 (moderate extracurricular activity), group 4: score 41 and higher (high extracurricular activity).

The data of maximal strength were not normally distributed and therefore nonparametric statistics were used. Kruskal-Wallis tests with post hoc Mann Whitney U tests were used to compare maximal strength among the five age categories and between boys and girls, as well as the interaction between gender and age. The comparison of maximal strength between dominant and non-dominant hand was done with the Wilcoxon signed rank test.

SFI showed a normal distribution and therefore parametric statistics were used. The differences between the SFI in boys and girls and among age groups as well as the interaction between gender and age were examined with ANOVA and post hoc tests (Tukey's HSD test). Statistical comparison of the SFI between the dominant and non-dominant hand and between the two grips was done with a paired t-test.

Spearman correlation coefficients were calculated to determine the correlation between maximal strength or muscle fatigue and 1) physical activity and 2) anthropometric variables: height, upper and lower arm length, hand length and weight and 3) between muscle fatigue and maximal strength. Correlations were interpreted as followed: 0.00 to 0.25 little or no relationship; 0.25 to 0.50 fair relationship, 0.50 to 0.75 moderate to good relationship and above 0.75 good to excellent relationship [25].

SASJMP PRO 11 software was used for data analysis and level of significance was set at $p<0.05$.

RESULTS

Participants

In total, 167 children were approached and 97 questionnaires of physical activity were filled out correctly and returned. Two children were excluded because of either a ventricular septum defect or a bony deformity of the elbow. One child was excluded, because of insufficient cooperation. Finally, 118 participants were included in the analysis, of which 24 participants were recruited in a former thesis project of K. De Koninck. Anthropometric data per age and gender category are reported in Table 1.

Age	N	Weight (kg)	Height (cm)	Upper arm length (cm)	Lower arm length (cm)	Hand length (cm)	Physical activity (sport score)
7-8 years; M	10	26.1 (2.3)	131.7 (3.8)	21.5 (2)	19 (1.5)	14.5 (0.5)	34 (19.5)
7-8 years; F	12	27.7 (5)	130.8 (9.1)	21 (2.5)	18 (1.5)	14 (1)	12.5 (10.5)
9-10 years; M	12	30.1 (5.6)	136.1 (5.6)	22.5 (1.5)	20 (2)	15.5 (1)	40.5 (23.5)
9-10 years; F	11	34.1 (7.6)	138.5 (5.3)	22 (2)	20.5 (1.5)	15.5 (1.5)	16 (9.5)
11-12 years; M	13	41.2 (7.5)	152.4 (6.5)	26 (2.5)	23 (2)	16.5 (1)	41.5 (20.5)
11-12 years: F	16	45.2 (11.1)	154.5 (9.5)	24 (2.5)	22 (1.5)	16.5 (1)	26 (18)
13-14 years: M	8	49.8 (11.7)	166.1 (13.7)	29.5 (3.5)	26.5 (2.5)	18.5 (2)	38 (25)
13-14 years: F	15	51 (11.1)	160.4 (6.3)	28.5 (3)	25 (1.5)	17.5 (1)	29.5 (22)
15-16 years: M	8	63.2 (8.5)	181 (3.3)	33 (2.5)	29.5 (1.5)	19.5 (1)	46.5 (18.5)
15-16 years: F	13	59.3 (10.6)	164.9 (5.7)	29 (2.5)	25.5 (1.5)	17.5 (1)	10 (16.5)
TOTAL	**118**	**42.6 (14.6)**	**151 (16.5)**	**25.5 (4.5)**	**22.5 (3.5)**	**16.5 (1.5)**	**28.5**

Table 1: Patient characteristics (Mean values (standard deviation)); M: Male; F: Female

Maximal strength

Descriptive data of SFI and maximal strength according to age and gender are presented in table 2. Nine measurements were excluded because the TPM did not appear within the first five seconds. The overall means (SD) of maximal strength were for the dominant hand grip 21.4 (9) kg, for the non-dominant hand grip 20.3 (9.1) kg, for the dominant pinch grip: 4.8 (1.7) kg and for the non-dominant pinch grip: 4.5 (1.16) kg.

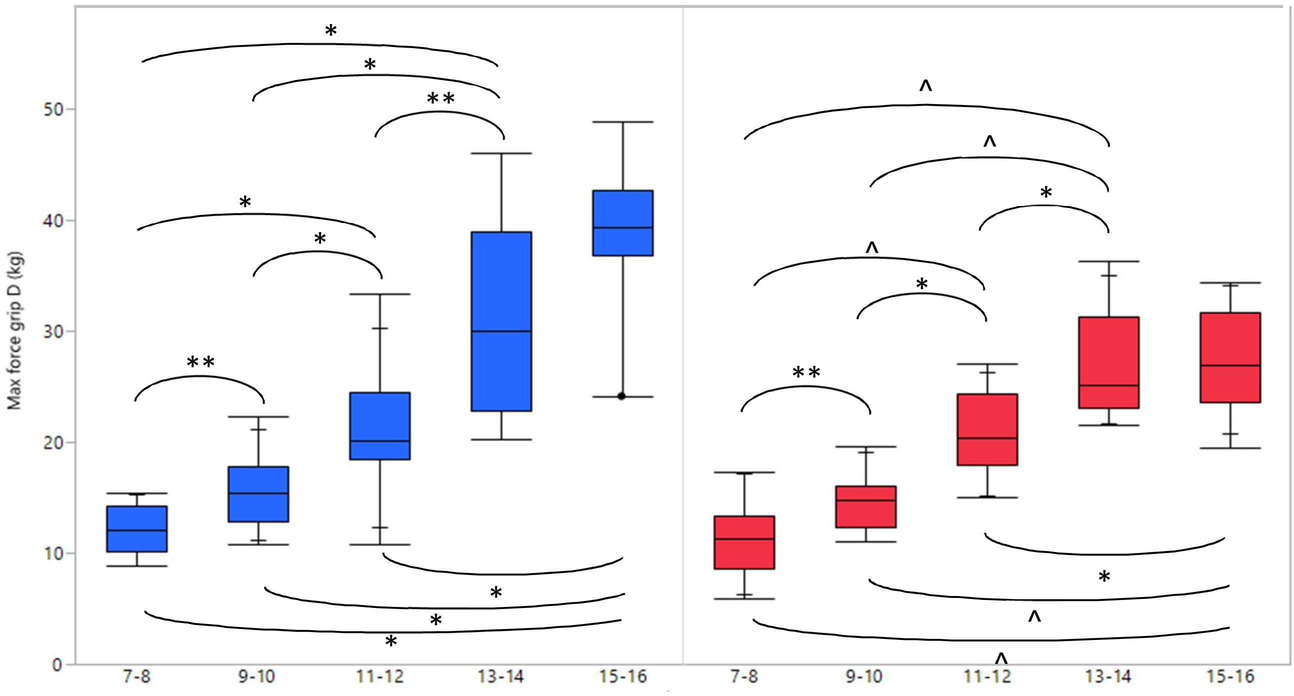
Statistical analysis showed an interaction between age and gender in maximal strength ($p<0.0001$), boys became stronger than girls with age (Figure 3). Post hoc tests showed that only at 15-16 years, boys were significantly stronger than girls for both the dominant and non-dominant hand grip (p=0.003). A significant increase in each age group in maximal strength was found for boys for the dominant (p=0.0002 – 0.02) and non-dominant hand grip (p=0.0003 – 0.03), except between the two oldest age groups (p=0.10 – 0.18). For girls, similar results were found for the dominant hand grip (p=<0.0001 – 0.02) but post hoc test showed that the non-dominant hand grip showed no significant increase between the two youngest age groups (p=0.07). An increase in pinch grip of both hands among the age groups was found for boys (p=0.0002 – 0.0004) and girls (p≤0.0001). Table II of the appendices provides the p-values of the maximal strength for the gender groups separately and combined.

Figure 6 provides the results regarding maximal strength according to hand dominance and. The maximal strength of both the pinch and hand grip for the dominant hand was significantly higher than the non-dominant hand for all ages (p<0.0001).The mean difference for the pinch grip was 0.24 with a SD of 0.05 and for the hand grip 1.1 with a SD of 0.21.

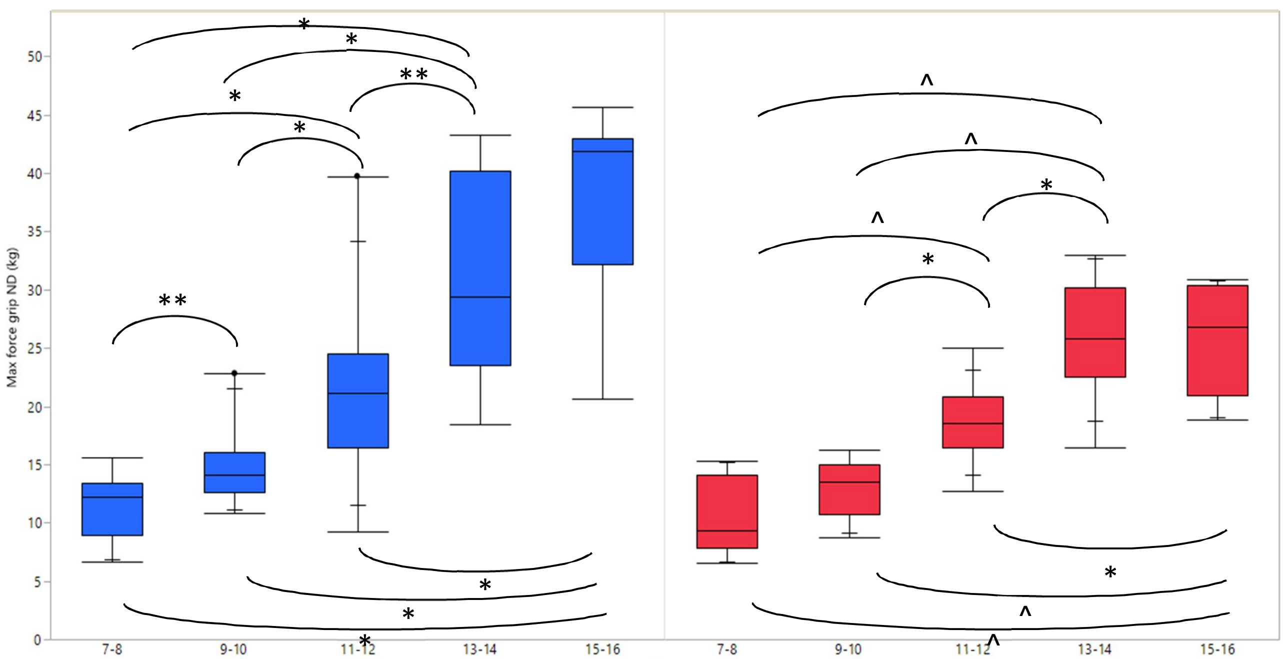
Age	**N**	**Maximal strength grip D**	**Maximal strength grip ND**	**Maximal strength pinch D**	**Maximal strength pinch ND**	**SFI grip D**	**SFI grip ND**	**SFI pinch D**	**SFI pinch ND**
7-8 years; M	10	12.1 (2.2)	11.4 (2.9)	3.2 (0.7)	3 (0.7)	43.7 (7.4)	46.2 (9.9)[a]	41.7 (8.5)	45.3 (7.7)[a]
7-8 years; F	12	11.4 (3.5)	10.4 (3.2)	3.1 (0.8)	2.8 (0.5)	42.4 (10.2)	46.4 (7.6)	41.3 (9.8)	43.3 (9.6)
9-10 years; M	12	15.4 (3.3)	14.8 (3.2)	3.7 (0.7)	3.6 (0.9)	40.9 (8.6)	49.1 (9)	37.9 (8)	42.9 (11.1)
9-10 years; F	11	14.6 (2.6)	13 (2.5)	3.7 (1)	3.3 (0.8)	38.9 (8.1)[b]	42.4 (7.5)	36.1 (5.5)	39.2 (7.2)
11-12 years; M	13	21.1 (5.5)	21.1 (7.3)	4.9 (1.2)	4.7 (1.3)	36.5 (9.8)	39 (8.4)	38.9 (9.9)[b]	38.9 (8.3)[b]
11-12 years: F	16	20.8 (3.9)	18.1 (3.1)	4.8 (1.2)	4.6 (1.1)	41.7 (9)	43.9 (7)	37.1 (5.3)	38.5 (6.5)
13-14 years: M	8	30.9 (9)	30.7 (8.8)	6 (2.2)	5.9 (2.4)	37.9 (6.1)	39.3 (7.3)	34.3 (7)	34 (4.3)
13-14 years: F	15	26.6 (4.7)	25.5 (4.7)	5.7 (0.8)	5.4 (0.9)	36 (6.8)	37.8 (6.6)	35.3 (8.9)	34.8 (5.3)
15-16 years: M	8	39 (7.1)	37.7 (8.4)	7.2 (1.8)	6.9 (1.6)	38.6 (6.7)	42.3 (7.8)	35.1 (8.3)	35.9 (9)
15-16 years: F	13	27.4 (4.7)	25.6 (4.6)	5.8 (1.2)	5.5 (1.2)	34.3 (12.8)	37.9 (10.7)	31.3 (7)	34.7 (8.9)
TOTAL	**118**	**21.4 (9)**	**20.3 (9.1)**	**4.8 (1.7)**	**4.5 (1.6)**	**39 (9.1)**	**42.3 (8.8)**	**36.9 (8.2)**	**39.7 (8.5)**

Table 2: Primary outcomes: SFI and maximal strength according to age and gender (Mean values (SD))

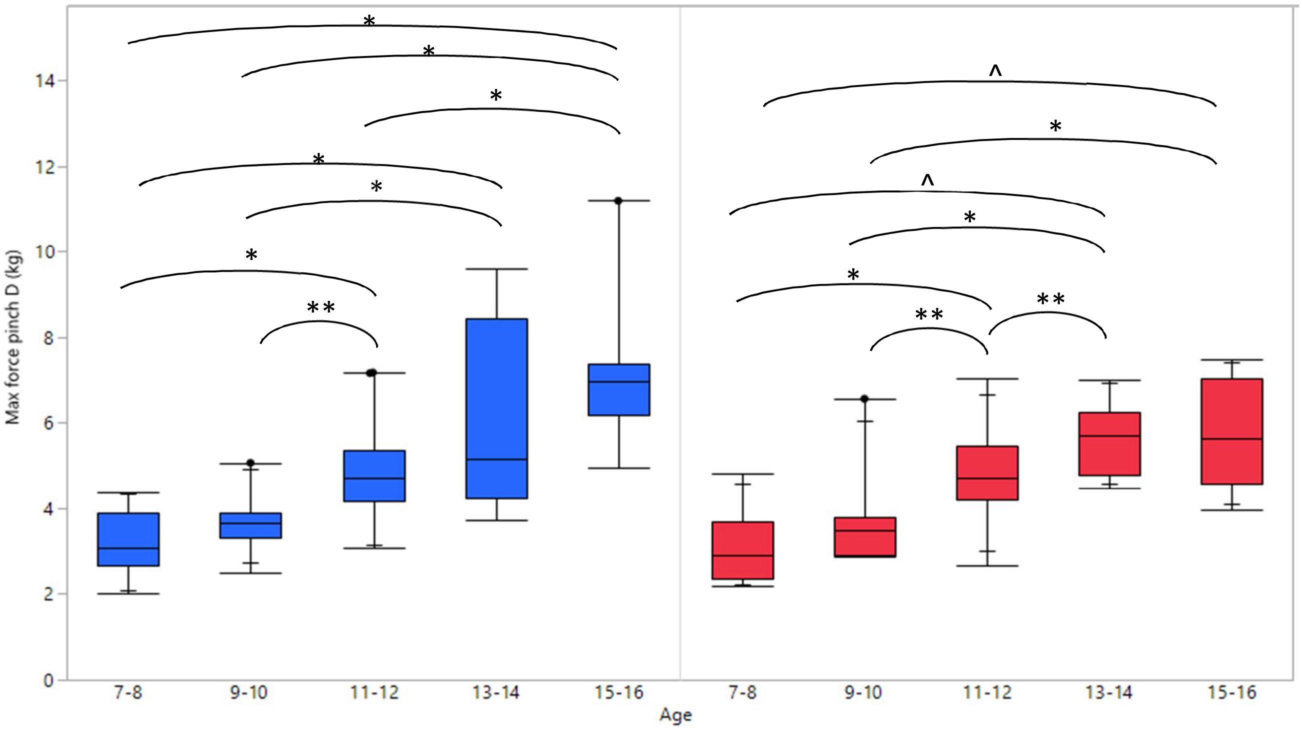
M: Male; F: Female; D: dominant hand; ND: non-dominant hand; SFI: in %; Maximal strength: in kg, [a] N=9, [b] N=10. [c] N= 12



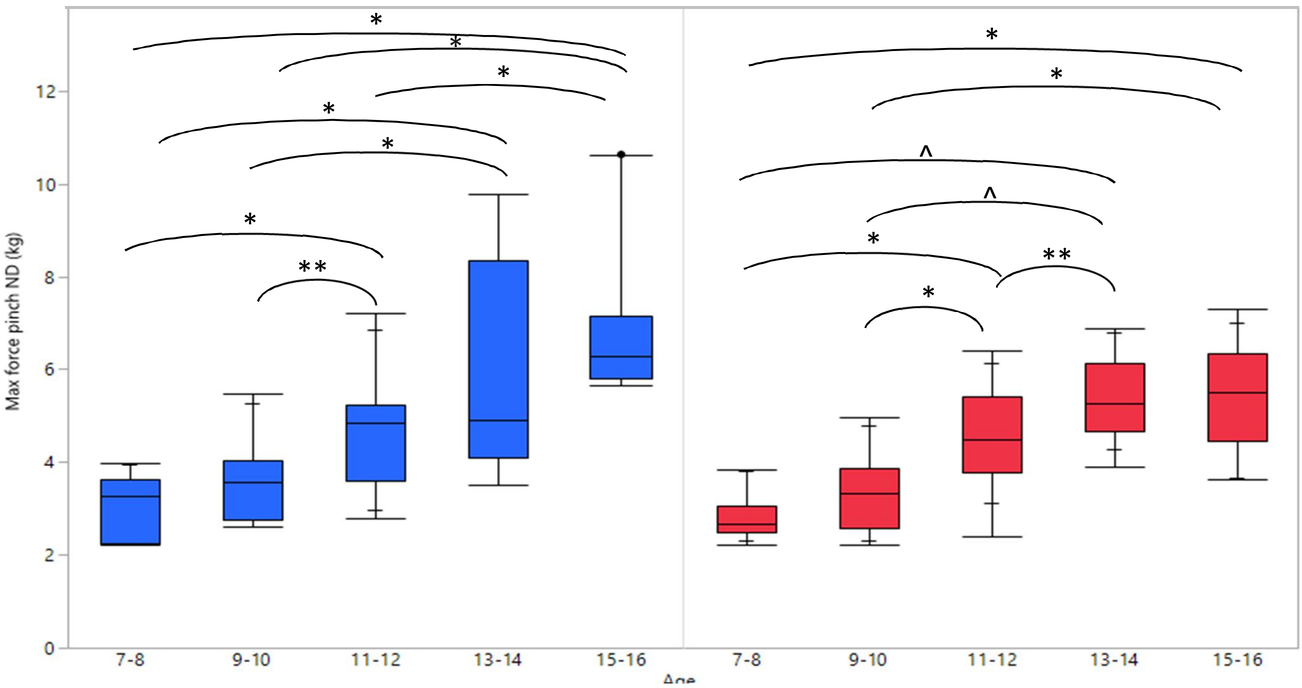
A. Maximal strength dominant hand grip



B. Maximal strength non-dominant hand grip

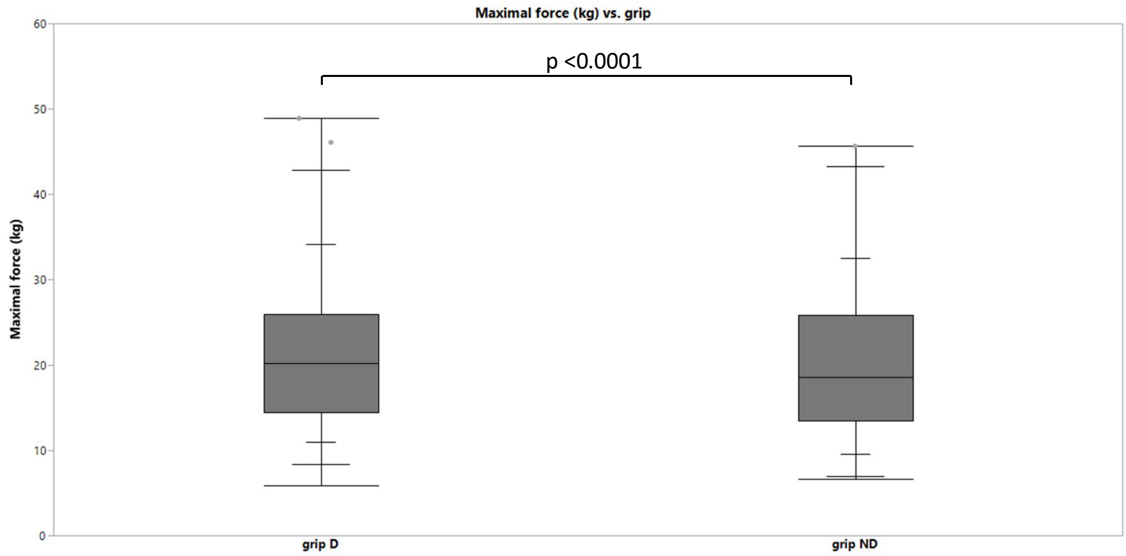


C. Maximal strength dominant pinch grip

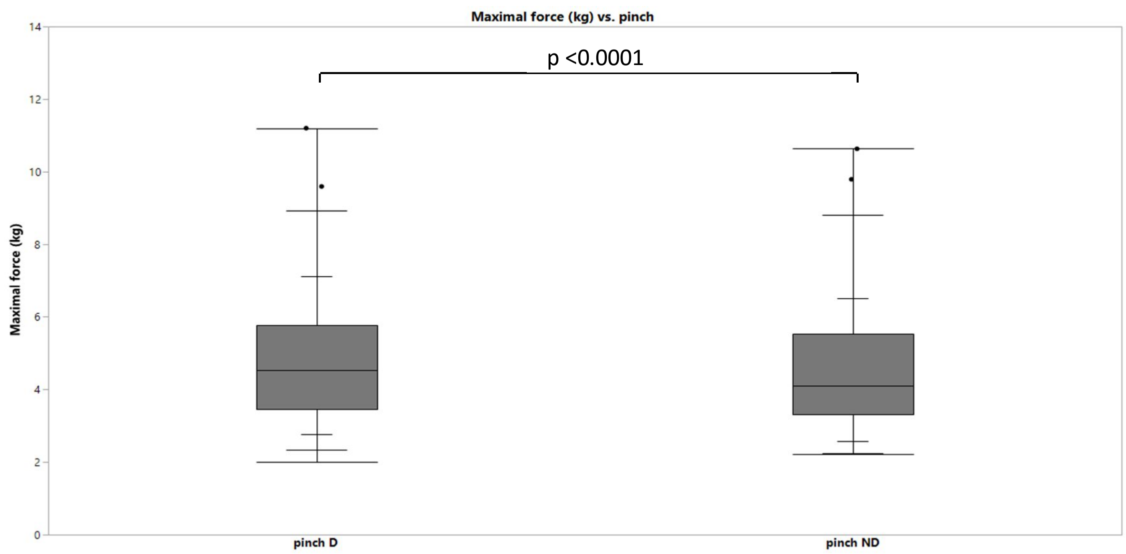


D. Maximal strength non-dominant pinch grip

Figure 5A-D: Boxplots of the interaction between gender (blue: boys – pink: girls) and age for maximal strength of the hand grip and pinch grip. The boxplots shows: minimum, first quartile, median, third quartile and maximum. The significant *p*-values of the Kruskal-Wallis test with post hoc Mann Whitney U test are shown: ^ p <0.0001, * p < 0.01 and ** p <0.05. Grip ND: hand grip non-dominant, grip D: hand grip dominant, pinch ND: pinch grip non-dominant, pinch D: pinch dominant.



A. Hand grip



B. Pinch grip

Figure 6A-B: Boxplot of the maximal strength of the hand grip (A) and pinch grip (B). The boxplots shows: minimum, first quartile, median, third quartile and maximum. The significant *p*-values of the Wilcoxon (signed) rank test are shown. Grip ND: hand grip non-dominant, grip D: hand grip dominant, pinch ND: pinch grip non-dominant, pinch D: pinch dominant.

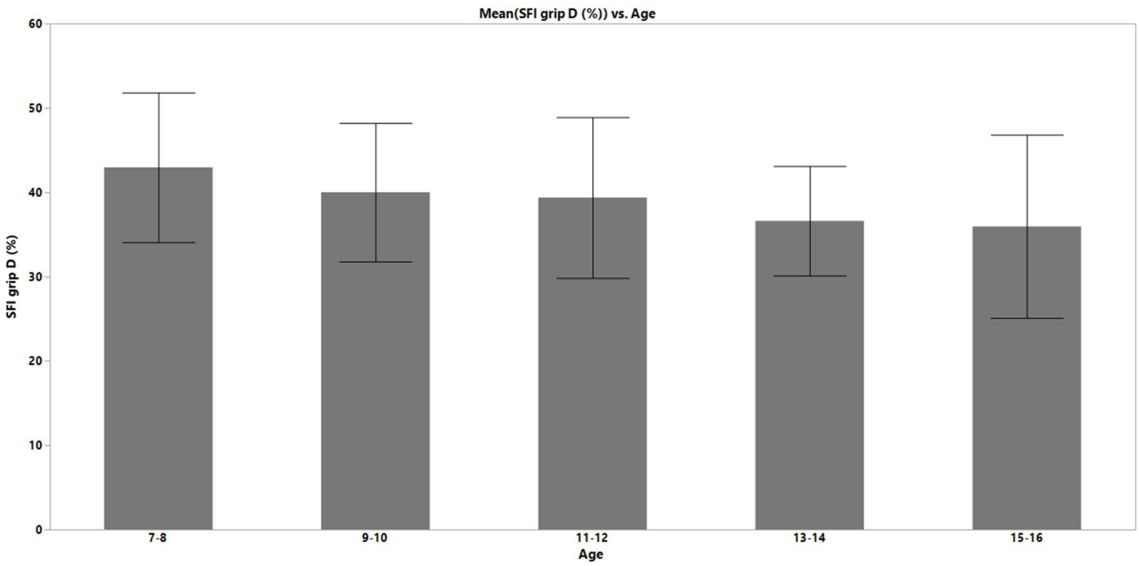
Static fatigue index (SFI)

The total group means (SD) of SFI were; dominant hand grip: 39% (9.1), non-dominant hand grip: 42.3% (8.8), dominant pinch grip: 36.9% (8.2), non-dominant pinch grip: 39.7% (8.5) (table 2).

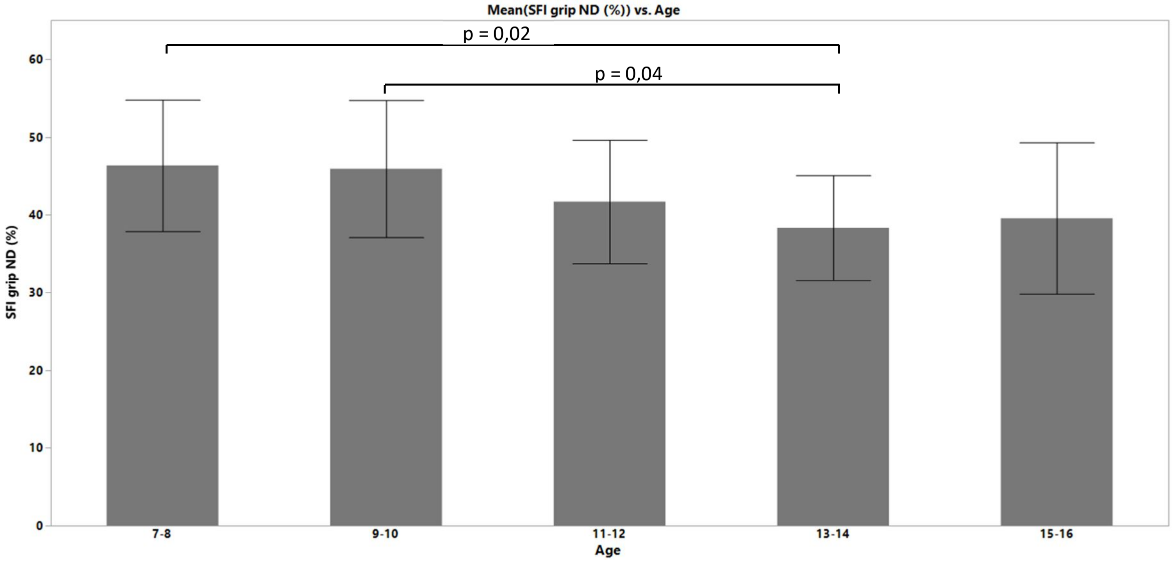
No interaction between gender and age for SFI was found, neither a significant difference between boys and girls.

Figure 7A-D displays the means and standard deviations for the five age groups. No significant differences were found for SFI of the dominant hand for hand grip. A significant decrease with age was found in SFI of the non-dominant hand grip from 7-8 years to 13-14 years (p=0.002), the dominant pinch grip (p=0.01) and the non-dominant pinch grip from 7-8 years to 15-16 years (p=0.0005). In detail, post hoc tests showed a significant decrease in SFI in the non-dominant hand grip between age groups 9-10 years and 13-14 years (p=0.04) and in the non-dominant pinch grip between age groups 7-8 years and 13-14 years (p=0.001).

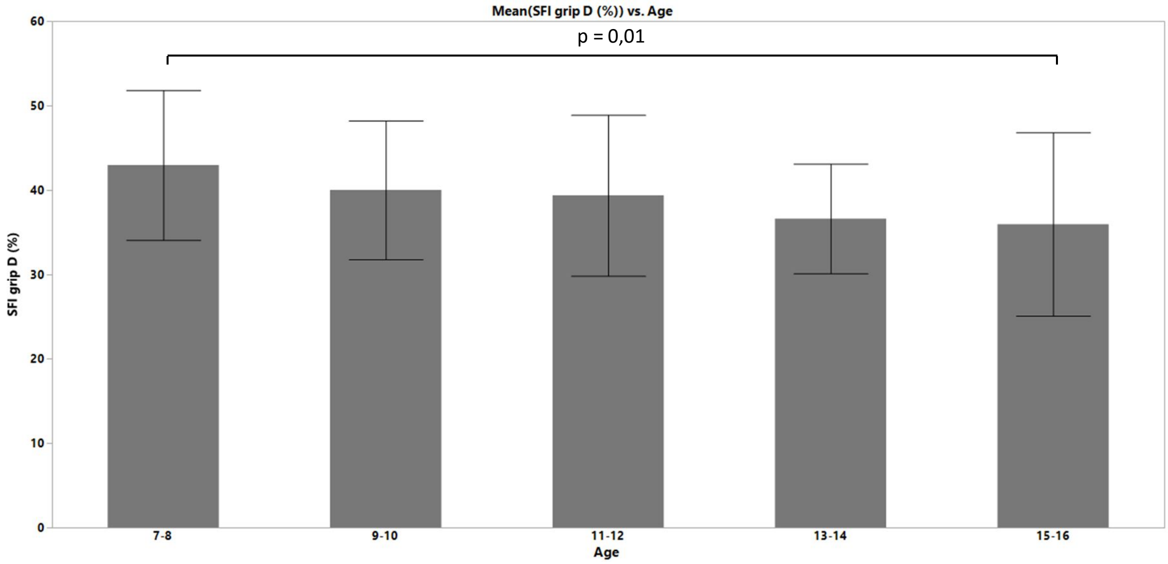
Figure 8 shows the results regarding SFI according to hand dominance and grip. The SFI was higher during both grips for the non-dominant hand compared to the dominant hand (hand grip: p<0.001; ND: 42%, D: 39%, pinch grip: p=0.02; ND: 39 %, 37 %). During the pinch grip test the SFI was significantly lower for both hands compared to the hand grip test (D: p=0.009, ND: p<0.0001).



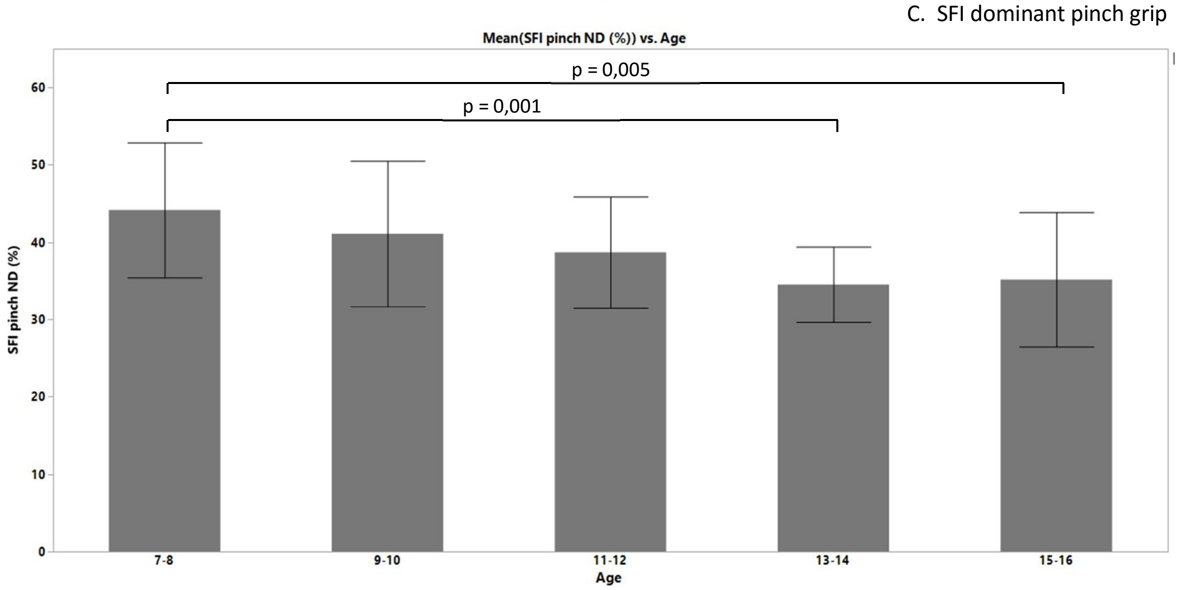
A. SFI dominant hand grip



B. SFI non-dominant hand grip



C. SFI dominant pinch grip



D. SFI non-dominant pinch grip

Figure 7A-D: Mean values and standard deviation of the static fatigue index of the hand grip and pinch grip. The *p*-values of ANOVA with post hoc test are shown. SFI: static fatigue index, grip ND: hand grip non-dominant, grip D: hand grip dominant, pinch ND: pinch grip non-dominant, pinch D: pinch dominant.

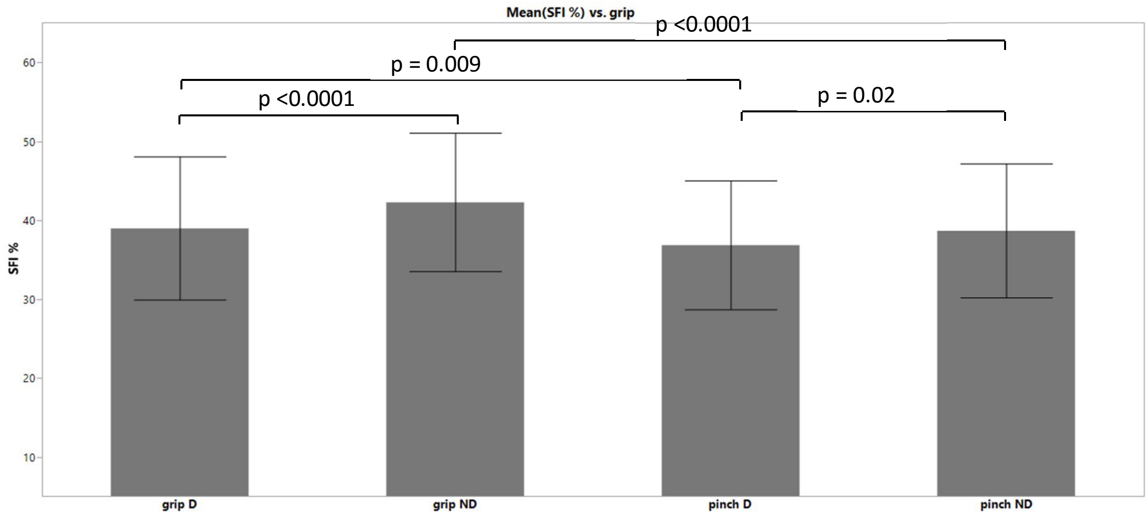


Figure 8: Mean values and standard deviation of the static fatigue index of the hand grip and pinch grip. The *p*-values of the (paired) t-test of significance difference are shown. SFI: static fatigue index, grip ND: hand grip non-dominant, grip D: hand grip dominant, pinch ND: pinch grip non-dominant, pinch D: pinch dominant.

Correlations

Table 3 displays the results of the correlation analysis between weight, height, upper arm length, lower arm length, hand length, physical activity and 1) maximal strength or 2) SFI and between maximal strength and SFI. Correlations were calculated for all age-groups and boys and girls together.

Moderate to excellent correlations were found between maximal strength for both hands and grips with anthropometric variables (r=0.74 – 0.90). No correlations were found for maximal strength with physical activity.

For muscle fatigue, only small to fair correlations were found for anthropometric variables (r=-0.19 – -0.37), meaning that higher SFI was associated with lower anthropometric values. The highest correlations were found for lower arm length and hand length (r=-0.28 – -0.34). No correlations were found for physical activity.

Finally, fair significant negative correlations between SFI and maximal strength were found for both hand and both grips, meaning that a higher SFI was associated with a lower maximal strength (r=-0.30 – -0.41).

	Grip	Hand	Weight	Height	Upper arm length	Lower arm length	Hand length	Physical activity	Maximal strength
Maximal strength	Hand	D[a]	**0.87**[$]	**0.90**[$]	**0.84**[$]	**0.90**[$]	**0.90**[$]	0.10	
		ND[a]	**0.85**[$]	**0.88**[$]	**0.84**[$]	**0.90**[$]	**0.88**[$]	0.14	
	Pinch	D[a]	**0.81**[$]	**0.81**[$]	**0.75**[$]	**0.78**[$]	**0.80**[$]	0.11	
		ND[b]	**0.80**[$]	**0.82**[$]	**0.74**[$]	**0.80**[$]	**0.79**[$]	0.12	
SFI	Hand	D	-0.19[*]	-0.23[*]	-0.24[**]	**-0.30**[$]	**-0.31**[**]	-0.10	**-0.34**[$]
		ND	-0.17	-0.24[**]	**-0.29**[**]	**-0.31**[$]	**-0.29**[$]	-0.08	**-0.41**[$]
	Pinch	D	-0.20[*]	-0.22[*]	**-0.25**[**]	**-0.28**[**]	**-0.29**[**]	0.01	**-0.35**[$]
		ND	**-0.31**[$]	**-0.33**[$]	**-0.37**[$]	**-0.34**[$]	**-0.34**[**]	-0.07	**-0.30**[**]

Table 3 correlation coefficients between maximal strength/SFI and weight/height/upper arm length/lower arm length/hand length/physical activity and SFI and maximal strength; [a] : N= 117, [b] : N=116, D: dominant; ND; non-dominant; SFI: static fatigue index, [*] significant with p ≤0.05, [**] significant with p <0.01, [$] significant with p<0.001.

DISCUSSION

The aim of this study was to provide normative data of muscle fatigue of hand and pinch grip as a reference for children and adolescents with motor disorders. Age and gender-specific data for muscle fatigue were established in 118 healthy Belgian children aged seven to 16 years. Secondly, the relation between muscle strength and muscle fatigue was investigated as well as the relation with age, gender, weight, upper and lower arm length, hand length, height and physical activity.

For the maximal hand grip strength, a significant difference was found between boys and girls, only for the age group 15-16 years. This is in contrast with the study of Ploegmakers et al. (2013), who found that boys were significantly stronger than girls in all age groups from four to 15 years. In the study of McQuiddy et al. (2015) an interaction was found between gender and age in both hand grip and pinch grip strength [26]. A possible explanation for the different findings is the smaller sample size used in our study compared with 2241 participants in the study of Ploegmakers et al. (2013) [27].

Furthermore, several studies found, in line with our results, an increasing grip strength in both hands among age [26-28]. The study of Ploegmakers et al. (2013) explained it by the growth spurt since there is a strong correlation between weight, height and strength. So in the most cases, older children are taller and have more weight, but these children are also stronger, because the muscle tissue increases and the lever arms of the muscles become longer when the body grows [27, 29].

The dominant hand was on average 5% stronger compared with the non-dominant hand in both grips. In adults it has been shown that the dominant hand is 10% stronger than the non-dominant hand, but this is only in right-handed persons [30]. Contrasting findings about hand dominance were found in several other studies, where no significant difference in hand strength was found between the dominant and non-dominant hand [26, 28]. A possible explanation for the different findings, is an imbalance in demographic variables and unequal number of right and left handed children and adolescents [28].

Next to maximal strength, this study also investigated muscle fatigue during a 30 seconds isometric hand grip and pinch grip. Results showed no difference in SFI between boys and girls of the same age groups. This findings are in accordance with the studies of Dipla et al.

(2009), Christos et al. (2006) and Skurvydas & Brazaitis (2010) [17, 18, 20]. These studies investigated muscle fatigue in the lower extremities with EMG and indexes.

Secondly, our study showed no significant differences between age groups for both girls and boys. Conversely the study of Dipla et al. (2009) investigated also the influence of age on muscle fatigue in the lower limbs and found more muscle fatigue in teen-males compared with boys and in teen-females compared with girls [17]. Furthermore, there was a decrease of the SFI with increasing age, but this was not a smooth decline and may be due to small age groups. A meta-analysis about muscle fatigue in adults found significantly more muscle fatigue in younger adults (18-45 years) compared with older adults (>55 years) in sustained isometric contractions. The decrease of muscle fatigue with increasing age might be the result of a greater proportion of type I muscle fibers in older persons [31]. However, studies on muscle fibers in children are sparse because of ethical reasons.

Differences for hand dominance were also found in this study. Both the dominant hand grip and pinch grip showed less muscle fatigue than the non-dominant grip. Contrasting results were found in the study of Nicolay et al. (2005), who reported that only one-fourth of the total group had less muscle fatigue in the dominant hand. The phenomenon that the dominant hand is stronger and shows more fatigue, can possibly be explained by the greater use of the dominant hand than the non-dominant hand in daily activities. Thereby, the muscle fibers in the dominant hand train the fast-twitch fibers more intensively [32].

Furthermore, SFI for the pinch grip was higher than SFI for the hand grip. This could be due to the use of more muscles during hand grip, whereby more motor units are recruited compared with pinch grip. If more motor units are recruited, it might take longer before every motor unit is recruited and before all motor units are exhausted, which means that force may be maintained longer. The study of Kukulka et al. (1981) described the differences in recruitment and rate of motor units in the biceps brachii and adductor pollicis. The results showed a greater recruitment of motor units in the biceps brachii, where new motor units were recruited till forces reached 80% MVC. While adductor pollicis recruited no motor units at forces higher than 50% MVC [33].

A second aim of this study was to investigate the correlations between 1) maximal strength, 2) SFI and anthropometric variables, physical activity as well as between maximal strength and SFI. Very low correlations were found between maximal strength and physical activity.

This can be due to the fact that many test persons did the same sports, such as football, tennis, dancing, volleyball and so on. So there was only a small variability in physical activities and most of the test persons did not sport more than seven hours per week. It might be hypothesized that children, who play a racquet sport for example, are stronger in their upper limbs than soccer players, but more research is necessary to study the correlation between physical activity and maximal strength. For example, more objective measurement methods of physical activity, like accelerometers can be used to find higher correlations between maximal strength and physical activity.

Moderate to excellent correlations were found between maximal strength and anthropometric variables. This is in accordance with several other studies, in which positive correlations were found between maximal strength of the hand grip and pinch grip and weight, height, lower arm length and hand length [27, 32, 34-36].

On the other hand, negative correlations were found between SFI and anthropometric variables, but these were little to fair and hereby this results are according to Nicolay et al. (2005), who stated that anthropometric measurements cannot predict muscle fatigue of the hand grip in adults with an age between 18 and 33 years [32]. Furthermore, no significant correlations were found between SFI and physical activity.

Finally, fair significant negative correlations between SFI and maximal strength were found for both hand and both grips, meaning that higher SFI was associated with lower maximal strength. In the study of Meldrum et al. (2007), no correlations were found between maximum strength and muscle fatigue of the hand grip in healthy adults [37].

Some limitations in this study need to be addressed. A first limitation is that the data were collected by two different testers. The verbal encouragement of the testers possibly differed and hereby also the effort of the child or adolescent. However, the testers were well trained and followed a standardized protocol, which should have limited the inter-rater variations.

A second limitation is that the reliability of the measuring method of sustained muscle strength can be questioned. However, according to a study of Van Meeteren et al. (2007) the reliability of the SFI during a 20 seconds isometric hand grip task in healthy young adults was moderate [38]. The test-retest reliability of the Jamar dynamometer, measuring maximum isometric muscle strength, in children aged four to 11 years was high according to a study of Van Den Beld at al. (2006) [39]. The inter-rater reliability was also high in young healthy

adults for both the Jamar hand-held dynamometer and the pinch gauge, testing hand grip and pinch grip strength respectively [40].
Finally, children would not be able to reach the maximal strength in isometric actions according the study of de Ste Croix et al. (2007). Inhibitory mechanisms would give children a feeling of discomfort caused by the rapid development of force during isometric actions [41]. So some results may vary due to the fact that some children and adolescents experienced discomfort during the 30s isometric grip test.

This study was the first study that investigated muscle fatigue in the upper limbs of TD children and adolescents. Future studies with larger sample sizes are needed to improve the understanding in the phenomenon of muscle fatigue in TD children and adolescents and its influencing factors. Further investigations of muscle fatigue are also necessary in children with common motor disorders, for example in children with central problems, such as CP and peripheral problems, such as NMD. This will be useful to gain better insights and to optimize the treatment of these children.

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APPENDIX I: Medical questionnaire

KU LEUVEN   UZ LEUVEN   universiteit hasselt

MEDISCHE VRAGENLIJST

Versie 1.1, 04/09/2014

TITEL

Manuele krachtregulatie, duurkracht en spiegelbewegingen bij typisch ontwikkelende Vlaamse kinderen en jongeren

Naam + voornaam kind: ....

Geboortedatum kind: ....

Heeft uw kind een chronische aandoening? (hart- of longziekte, motorische stoornis of andere)

- Ja
- Neen

Indien ja, welke? ……………………………………

Neemt uw kind op regelmatige basis medicatie?

- Ja
- Neen

Indien ja, welke? …………………………………….

Hoeveel keer per week doet uw kind aan sport?

- Nooit
- Bijna nooit
- Één keer per week   Welke sport? ....
- Meer dan één keer per week   Welke sport? ....

Appendix II: Tables maximal strength among age groups for boys, girls and combined

A. Dominant hand grip

	7-8	*9-10*	*11-12*	*13-14*
9-10	**0.001**			
11-12	**<0.0001**	**<0.0001**		
13-14	**<0.0001**	**<0.0001**	**<0.0001**	
15-16	**<0.0001**	**<0.0001**	**<0.0001**	0.09

A1: Both boys and girls

	7-8	*9-10*	*11-12*	*13-14*
9-10	**0.02**			
11-12	**0.0005**	**0.005**		
13-14	**0.0004**	**0.0004**	**0.01**	
15-16	**0.0004**	**0.0002**	**0.0004**	**0.10**

A2: Only boys

	7-8	*9-10*	*11-12*	*13-14*
9-10	**0.02**			
11-12	**<0.0001**	**0.0004**		
13-14	**<0.0001**	**<0.0001**	**0.002**	
15-16	**<0.0001**	**<0.0001**	**0.002**	0.58

A3: Only girls

B. Non-dominant hand grip

	7-8	*9-10*	*11-12*	*13-14*
9-10	**0.004**			
11-12	**<0.0001**	**<0.0001**		
13-14	**<0.0001**	**<0.0001**	**<0.0001**	
15-16	**<0.0001**	**<0.0001**	**<0.0001**	0.35

B1: Both boys and girls

	7-8	*9-10*	*11-12*	*13-14*
9-10	**0.03**			
11-12	**0.0005**	**0.006**		
13-14	**0.0004**	**0.0004**	**0.01**	
15-16	**0.0004**	**0.0003**	**0.002**	0.18

B2: Only boys

	7-8	*9-10*	*11-12*	*13-14*
9-10	0.07			
11-12	**<0.0001**	**<0.0001**		
13-14	**<0.0001**	**0.0002**	**0.0003**	
15-16	**<0.0001**	**<0.0001**	**0.0007**	1,00

B3: Only girls

C. Dominant pinch grip

	7-8	*9-10*	*11-12*	*13-14*
9-10	**0.03**			
11-12	**<0.0001**	**0.0003**		
13-14	**<0.0001**	**<0.0001**	**0.02**	
15-16	**<0.0001**	**<0.0001**	**0.001**	0.20

C1: Both boys and girls

	7-8	*9-10*	*11-12*	*13-14*
9-10	0.20			
11-12	**0.001**	**0.02**		
13-14	**0.002**	**0.003**	0.45	
15-16	**0.0004**	**0.0003**	**0.004**	0.27

C2: Only boys

	7-8	*9-10*	*11-12*	*13-14*
9-10	0.10			
11-12	**0.0005**	**0.01**		
13-14	**<0.0001**	**0.0003**	**0.03**	
15-16	**<0.0001**	**0.0004**	0.06	0.93

C3: Only girls

D. Non-dominant pinch grip

	7-8	*9-10*	*11-12*	*13-14*
9-10	**0.02**			
11-12	**<0.0001**	**0.0004**		
13-14	**<0.0001**	**<0.0001**	**0.002**	
15-16	**<0.0001**	**<0.0001**	**0.002**	0.58

D1: Both boys and girls

	7-8	*9-10*	*11-12*	*13-14*
9-10	0.16			
11-12	**0.003**	**0.03**		
13-14	**0.001**	**0.01**	0.30	
15-16	**0.0002**	**0.0002**	**0.003**	0.19

D2: Only boys

	7-8	*9-10*	*11-12*	*13-14*
9-10	0.07			
11-12	**0.0002**	**0.0003**		
13-14	**<0.0001**	**<0.0001**	**0.04**	
15-16	**0.0001**	**<0.0001**	0.08	0.65

D3: Only girls

Auteursrechtelijke overeenkomst

Ik/wij verlenen het wereldwijde auteursrecht voor de ingediende eindverhandeling:
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Datum: **16/06/2016**