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Muscle-tendon properties and functional gait outcomes in clubfoot patients with and without a relapse compared to typically developing children

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ABSTRACT

Background: Altered muscle-tendon properties in clubfoot patients could play a role in the occurrence of a relapse and negatively affect physical functioning. However, there is a lack of literature about muscle-tendon properties of clubfoot relapse patients.

Research question: The aim of this study was to determine whether the muscle architecture of the medial gastrocnemius and the morphology of the Achilles tendon differ between typically developing children (TDC) and clubfoot patients with and without a relapse clubfoot and to determine the relationships between morphological and functional gait outcomes.

Methods: A cross-sectional study was carried out in clubfoot patients treated according to the Ponseti method and TDC aged 4–8 years. A division between clubfoot patients with and without a relapse was made. Fifteen clubfoot patients, 10 clubfoot relapse patients and 19 TDC were included in the study. Morphologic properties of the medial head of the Gastrocnemius muscle and Achilles tendon were assessed by ultrasonography. Functional gait outcomes were assessed using three-dimensional gait analysis. Mean group differences were analysed with ANOVA and non-parametric alternatives. Relationships between functional and morphologic parameters were determined for all clubfoot patients together and for TDC with Spearman's rank correlation.

Results: Morphological and functional gait parameters did not differ between clubfoot patients with and without a relapse, with exception of lower maximal dorsiflexor moment in clubfoot relapse patients. Compared to TDC, clubfoot and relapse patients did show lower functional gait outcomes, as well as shorter and more pennate muscles with a longer Achilles tendon. In all clubfoot patients, this longer relative tendon was related to higher ankle power and plantarflexor moment.

Significance: In clubfoot and relapse patients, abnormalities in morphology did not always relate to worse functional gait outcomes. Understanding these relationships in all clubfoot patients may improve the knowledge about clubfoot and aid future treatment planning.

1. Introduction

Congenital clubfoot is a complex deformity in which several anomalies in the tendons, muscles, and ligaments of the foot and lower leg are present [1]. Varus of the hindfoot, adductus of the forefoot, cavus and equinus give the foot its typical appearance. The recommended treatment is the Ponseti method [3], which has high long-term success rates of 78%–98% [4,5]. The Ponseti method consists of manipulation, serial casting, mostly followed by an Achilles tenotomy and a period of bracing. Despite good initial outcome of the Ponseti method after the casting phase, 11%–47% of the patients develop a relapse, in which one or more of the original characteristics of the clubfoot reoccur [4].

In the initial treatment phase, up to 90% of the clubfoot patients need an Achilles tenotomy to correct residual equinus in the hindfoot and increase passive dorsiflexion [4,7]. Clinical and ultrasonographical examinations show Achilles tendon (AT) continuity within 3–6 weeks after

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dissection [8,9] and complete tendon healing within one year [10,11]. Even though these findings suggest good healing of the AT after tenotomy, there are still abnormalities in tendon and muscle characteristics in clubfoot patients. Short-term results show that clubfoot patients have longer AT after tenotomy [12]. Additionally, shorter and thinner calf muscles have been observed on the long term as compared to typically developing children (TDC) [12,13]. Furthermore, irregularities in AT structure and shape were found shortly after tenotomy and remained present even 8 years post-tenotomy [11,14]. Moreover, treatment-resistant clubfeet have a smaller total muscle volume of the lower leg, with more fat infiltration compared to clubfoot patients without a relapse [15].

Changes in morphological characteristics of the Gastrocnemius muscle and AT in clubfoot patients could negatively affect physical functioning. For instance, muscle and tendon length together with the pennation angle and fibre length are known to affect force generation of the muscle [16]. Previous studies reported deficits in physical functioning of clubfoot patients, i.e. walking capacity was 21% lower than TDC [17]. Moreover, ankle power and range of motion (ROM) are diminished in clubfoot patients when compared to TDC [18,19].

However, the relation between tendon and muscle morphology and deficits in functional gait outcomes in clubfoot patients has not yet been investigated. Muscle and tendon characteristics play a potential role in the occurrence of a relapse clubfoot [20]. Therefore, it is important to differentiate between successfully treated patients and patients who need additional treatment following the Ponseti method. The aim of this study was to determine whether the muscle architecture of the medial gastrocnemius and the morphology of the AT differ between TDC and clubfoot patients with and without a relapse clubfoot. Furthermore, the relation between gait analysis as functional gait outcomes and tendon and muscle parameters as morphological outcome is determined.

2. Methods

2.1. Study population

Between May 2017 and January 2020, a cross-sectional study was conducted in a convenience sample of clubfoot patients and TDC aged 4–8 years. This study was approved by the Medical Research Ethics Committee United (MEC-U) and local review board [M15-1557/nWMO 2014-69]. TDC were recruited via the network of the researchers and uni- and bilateral idiopathic clubfoot patients were recruited via the treating orthopaedic surgeon of the Máxima MC hospital in Veldhoven and the Catharina Hospital in Eindhoven (AB). Informed consent was obtained from both parents before the measurements.

Clubfoot patients were included when they had idiopathic, Ponseti-treated uni- or bilateral clubfoot. All patients underwent Achilles tenotomy as part of their primary treatment. A division between clubfoot patients with a relapse (relapse patients) and without a relapse (clubfoot patients) was made by the treating orthopaedic surgeon. A relapse clubfoot was defined as having a reoccurrence of one or more of the symptoms of the original clubfoot after good initial correction of the clubfoot which needed additional treatment [21]. Additional treatment included bracing, or surgical treatment, possibly in combination with casting and/or physiotherapy. A renewed Achilles tenotomy early in life (before the age of three) was not considered as additional treatment. Clubfoot and relapse patients were excluded when they already received additional treatment before the measurements of this study. Furthermore, patients were excluded when they had syndromic or neurogenic clubfoot or when they had severe contractures. Both (relapse) clubfoot patients and TDC were excluded from the study if they were not able to follow instructions or had another disorder that impaired walking.

2.2. Measurements

All measurements were performed in the movement analysis laboratory at Fontys University for Applied Sciences in Eindhoven, except for passive dorsiflexion of the ankle, which was measured only in clubfoot and relapse patients by the treating orthopaedic surgeon during their regular visit to the hospital. To assess the quality of the AT and medial head of the gastrocnemius muscle, ultrasonography was used. Ankle function was evaluated with three-dimensional gait analysis. In clubfoot and relapse patients, the (most) affected leg was evaluated and in TDC the right leg was measured.

2.2.1. Ultrasound

Static ultrasonography was performed with a Toshiba Xario 200 ultrasound system and PLU1005 14L5 transducer (10 MHz) by two researchers (LG and LO). Ultrasound settings were optimised manually to identify the structures under investigation.

Children lay in a prone position on the examination bench with their foot hanging at their natural resting angle, to allow for a relaxed state of the muscle-tendon complex. Transverse and longitudinal images of the AT were made every 1 cm from the distal end of the lateral malleolus to the myotendinous junction. Transverse and longitudinal images of the medial gastrocnemius muscle were made every 2 cm between the myotendinous junction and the fibula head.

After data-acquisition, two assessors (SG and SW) extracted relevant parameters from the ultrasound images using Jivex DICOM Viewer (VISUS Health IT GmbH, version 5.2). Moderate to excellent inter- and intra-reliability was found for the assessment of muscle-tendon characteristics, ranging from 0.622 to 0.995. To compare the groups, data from the second assessment made by the lead author (SW) was used.

Muscle and tendon length were also determined separately using the myotendinous junction and reference points at the level of the lateral malleolus and fibula head, to calculate the ratio between muscle and tendon length. The muscle and tendon thickness and anatomical cross-sectional area (CSA) were measured at its thickest portion. Furthermore, fibre length and pennation angle of the muscle fascicles were determined in the thickest portion of the muscle belly where the myotendinous junction was no longer visible. AT quality was determined by two assessors who individually checked the longitudinal images of the Achilles tendon for irregularities. When an irregularity was present, the length, echogenicity, texture, the presence of focal thickening, and the distance to the calcaneal insertion were assessed similar to the study of Maranho et al. [11]. Echogenicity of the irregularity was assessed by visually comparing the echo-intensity of the irregularity with the echo-intensity of the surrounding tendinous tissue.

2.2.2. Gait analysis

Prior to the ultrasound measurement, kinematic and kinetic data was obtained using an active 3D motion analysis system (Codamotion Ltd., CX1, sampling rate: 100 Hz), and an integrated force plate (Advanced Mechanical Technology, Inc., OR 6–7, sampling frequency: 500 Hz). The active markers were placed according to an extended Helen-Hayes model by two researchers (LG and LO) [22]. The model consisted of 19 markers, including an additional marker cluster on the upper leg. Children were asked to walk at self-selected speed across the 8 m-walkway and were unaware of the force platform. For every participant, 3–5 good trials were included in further data-analysis. Data-analysis was performed in Odin (Codamotion Ltd.) and MATLAB r2019b (The MathWorks Inc.). Main functional outcomes from the gait analysis were maximum ankle power (W/kg), maximal plantarflexor moment (Nm/kg) and maximum ankle dorsiflexion during walking (°). Maximal ankle power and maximal plantarflexor moment are functional kinetic parameters reflecting the force production capacity. The maximum ankle dorsiflexion during walking can be related to the stretching of the muscle-tendon complex and thereby the maximal length of the complex. A three-dimensional inverse dynamics approach was used to calculate internal ankle moments from ground reaction force and marker data. Ankle power was calculated from angular velocity and ankle moment.

2.3. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 23. Normality of continuous parameters was checked using a Shapiro-Wilk test. Continuous variables were presented as mean ± standard deviation and categorical variables were presented as count (n) and percentage (%). Comparison between the three study groups was done with ANOVA and χ^2-tests or nonparametric tests, if applicable. Furthermore, Bonferroni corrected post-hoc tests were performed to determine specific differences. To determine the effect sizes, partial eta squared (η_p^2) was calculated. Effect sizes between 0.01 and 0.05 were considered small, between 0.06 and 0.13 medium and > 0.14 large. Spearman's rank correlations were determined to assess the relation between functional and morphological outcomes, as data was not normally distributed. Correlations were determined for TDC and for all clubfoot patients together, including clubfoot and relapse patients. Relationships between muscle-tendon parameters that were related to length (e.g. fibre length and muscle-tendon ratio) and kinematic parameters were expected, but not with kinetic parameters. Therefore, the relationships between the length-related muscle-tendon parameters and kinetic parameters were omitted from the analyses. Correlations were considered weak between 0.3 and 0.5, moderate between 0.5 and 0.7 and strong if higher than 0.7.

3. Results

3.1. Demographical characteristics

Ultrasound data was obtained for 50 children who met the inclusion criteria. Six children had no kinematic or kinetic data due to technical problems. Therefore, 44 children, of which 19 TDC, 15 clubfoot patients and 10 relapse patients were included. No differences in demographic characteristics were seen between TDC and clubfoot and relapse patients (Table 1). Relapse patients did show lower passive dorsiflexion compared to clubfoot patients. For a detailed description of the relapse characteristics of the clubfoot patients in the relapse group, see Appendix 1.

Table 1
Demographic characteristics of TDC, clubfoot patients and relapse clubfoot patients, presented in mean ± standard deviation, and count (percentage).

	TDC (n = 19)		Clubfoot (n = 15)		Relapse clubfoot (n = 10)	
Age [years]	5.79	±1.40	5.13	±1.25	5.70	±1.57
Height [m]	1.19	±0.11	1.13	±0.08	1.15	±0.11
Weight [kg]	21.82	±5.28	20.15	±2.79	21.10	±4.28
Gender [men n (%)]	0.11	(58)	12	(80)	6	(60)
Clubfoot characteristics						
Affected [uni n (%)]	–		9	(60)	4	(40)
Passive dorsiflexion [°]	–		19.67	±13.95[a]	3.50	±11.07
Initial treatment [n (%)]						
Achilles tendon tenotomy	–		15	(100)	10	(100)
re-Achilles tendon tenotomy[b]	–		5	(33)	3	(30)
Planned relapse treatment [n (%)]						
Tibialis anterior tendon transfer	–		–		2	(20)
Anterior distal tibial epiphysiodesis	–		–		3	(30)
Additional bracing	–		–		5	(50)

TDC = typically developing children.
[a] < 0.01 vs. relapse clubfoot.
[b] re-Achilles tendon tenotomy was performed up to 1–2 years after birth.

3.2. Muscle tendon characteristics

Muscle-tendon properties of clubfoot and relapse patients were different compared to TDC (Table 2). However, clubfoot and relapse patients had similar muscle and tendon characteristics. A lower muscle-tendon ratio was found in clubfoot and relapse patients when compared to TDC, indicating that clubfoot and relapse patients show a relatively longer AT tendon due to a shorter medial Gastrocnemius muscle belly. Furthermore, clubfoot and relapse patients had thinner muscles with a smaller CSA and shorter muscle fascicles arranged at a larger pennation angle compared to TDC. Large effect sizes were found for almost all muscle-tendon characteristics, except for tendon thickness (Table 2).

When examining the qualitative characteristics, significantly more relapse patients showed tendon irregularity. More specifically, all relapse patients showed irregularity of the AT, while only 11 out of 15 clubfoot patients and 3 out of 19 TDC showed irregularities. A description of the irregularities is presented in Table 3, and an example of a tendon irregularity is shown in Fig. 1.

3.3. Functional gait analysis

Walking speed was comparable for TDC, clubfoot and relapse patients. Deficits in ankle kinetics during gait were observed for clubfoot and relapse patients compared to TDC (Table 2). Furthermore, relapse patients had a lower maximum dorsiflexion angle during walking compared to TDC. Also, relapse patients showed a lower maximum dorsiflexion moment when compared to clubfoot patients.

3.4. Relationships between morphological and gait characteristics

As the relationships were similar for clubfoot and relapse patients, all clubfoot patients were taken together. A positive relationship between muscle CSA and maximum plantarflexor moment was found for both TDC and all clubfoot patients, where a higher muscle CSA indicated a higher plantarflexor moment (Table 4, Fig. 2A). However, some relationships between morphological and gait characteristics seem to differ between all clubfoot patients and TDC (Table 4). In TDC, a higher muscle-tendon ratio is related to a higher maximum dorsiflexion during walking, but this relation was not observed in clubfoot patients (Fig. 2B). Besides, higher muscle-tendon ratio is related to lower ankle power and lower plantarflexor moment in all clubfoot patients, while in TDC no relationships were found (Fig. 2C, D).

4. Discussion

In this study, different morphological properties of the muscle tendon unit and lower functional gait outcomes were found for clubfoot and relapse patients when compared to TDC. Clubfoot and relapse patients had shorter medial gastrocnemius with shorter and more pennate muscle fascicles. In addition, more irregularities in the AT in a shorter relative tendon were found. Also, clubfoot and relapse patients showed a decrease in maximal ankle power, maximum dorsi- and plantarflexor moment and maximum dorsiflexion during walking, which is in line with previous research [18,19]. Furthermore, almost no differences were found between clubfoot and relapse patients.

Clubfoot and relapse patients had a lower muscle-tendon ratio, due to a shorter medial gastrocnemius muscle with a longer AT when compared to TDC. All clubfoot patients in our study underwent at least an Achilles tenotomy at approximately one month after birth as part of the Ponseti method. During this tenotomy, the AT was cut to correct residual equinus. Afterwards, the tendon regrows at the lengthened position [11], which could partly explain the relative longer tendon observed in clubfoot and relapse patients in this study. In line with these results, other studies reported that clubfoot patients have a longer AT and shorter muscle belly post-tenotomy [12]. However, Achilles tenotomy does not seem to be the only cause of tendon lengthening and

Table 2
Morphological and gait characteristics of the Achilles tendon and Med. Gastrocnemius for TDC, clubfoot patients and relapse clubfoot patients, presented in mean ± standard deviation.

	TDC (n = 19)		Clubfoot (n = 15)		Relapse clubfoot (n = 10)		Effect size
Morphological assessment							
Achilles tendon							
Length [mm]	96.4	± 19.6	123.5	± 21.3 * *	111.7	± 25.7	0.243
Thickness [mm]	4.0	± 0.6	3.8	± 0.8	3.4	± 0.3 * *	0.127
CSA [mm^2]	33.4	± 8.6	30.1	± 6.4	23.2	± 5.4 * *	0.240
Med. Gastrocnemius							
Length [mm]	152.5	± 23.4	111.8	± 18.1 * *	121.3	± 26.5 * *	0.420
Thickness [mm]	12.4	± 1.5	10.6	± 1.5 *	9.8	± 2.1 * *	0.307
CSA [mm]	495.5	± 106.2	389.6	± 74.84 * *	350.7	± 139.5 * *	0.269
Pennation angle [°]	13.8	± 2.7	18.5	± 3.1 * *	17.7	± 3.5 * *	0.355
Fascicle length [mm]	52.5	± 7.3	34.5	± 2.5 * *	33.7	± 9.0 * *	0.670
Muscle-tendon complex							
Ratio [muscle/tendon]	0.61	± 0.07	0.48	± 0.06 * *	0.52	± 0.05 * *	0.504
Gait assessment							
Velocity [m/s]	1.07	± 0.16	0.99	± 0.07	1.03	± 0.12	0.069
Normalised stride length§	1.54	± 0.11	1.46	± 0.12	1.47	± 0.12	0.101
Max. ankle dorsiflexion [°]	8.39	± 5.04	4.50	± 7.11	2.40	± 4.54 * *	0.166
Max. ankle power [W/kg]	2.28	± 0.67	1.71	± 0.43 *	1.35	± 0.40 * *	0.345
Max. dorsiflexor moment[Nm/kg]	0.06	± 0.01	0.05	± 0.01 *ˆ	0.03	± 0.02 * *	0.445
Max. plantar flexor moment [Nm/kg]	0.88	± 0.15	0.68	± 0.14 * *	0.61	± 0.16 * *	0.386

TDC, typically developing children; CSA, anatomical cross-sectional area. *< 0.05 vs. TDC, ** < 0.01 vs. TDC, ˆ < 0.05 vs. relapse clubfoot, § Normalised for leg length.

Table 3
Characteristics of the tendon for the TDC, clubfoot and relapse group presented in mean ± standard deviation and count (percentage). Only tendons in which an irregularity was found were described (n – number of tendons with an irregularity).

	TDC (n = 3)		Clubfoot (n = 11)		Relapse clubfoot (n = 9)[a]	
Heterogeneous texture [n (%)]	–		5	(45)	4	(45)
Echogenicity [abnormal n (%)]	1	(33)	10	(91)	9	(100)
n (%) Hypoechogenic	1	(33)	5	(45)	4	(45)
n (%) Hyperechogenic	–		2	(18)	1	(10)
n (%) Both hypo-/hyperechogenic	–		3	(27)	4	(45)
Thickening [yes n (%)]	2	(67)	2	(18)	4	(45)
Length of irregularity [mm]	14.6	± 4.8	23.0	± 10.7	26.2	± 13.3
Distance from distal end of the lateralmalleolus [% of tendon length]	6.5	± 6.3	10.7	± 10.5	10.9	± 12.0

TDC = typically developing children.
[a] Ultrasound images of one patient from the relapse group were excluded because qualitative analysis of the longitudinal images of the Achilles tendon could not be performed.

muscle shortening in clubfoot and relapse patients. Even before Achilles tenotomy was performed, shorter calf muscles were observed in patients with clubfeet, when the affected side was compared to the nonaffected side of unilateral clubfoot patients and TDC [1,13].

The longer relative tendon and shorter muscles in clubfoot and relapse patients coincide with shorter muscle fascicles in clubfoot and relapse patients compared to TDC. Shorter muscle fascicles potentially contain less sarcomeres in series [23]. Therefore, less lengthening and shortening of the fascicles is possible resulting in a lower operating range and a lower maximum shortening velocity, which both negatively impact the optimal functioning of the muscle. Next to shorter muscle fascicles, a larger pennation angle was found for clubfoot and relapse patients when compared to TDC. To regain better muscle functioning, adaptation of the internal muscle structure could have caused the pennation angle to increase [23]. A larger pennation angle allows more parallel muscle fascicles within the same muscle volume which is advantageous for maximal force generation [24] and thus compensates for the shorter muscle. However, the larger pennation angle also negatively influences the effective force transmission to the foot and together with the shorter fascicles might reduce the capacity to generate high plantarflexor moment during push-off.

This study found a smaller CSA of the medial gastrocnemius muscles in all clubfoot patients when compared to TDC, but not between clubfoot patients with and without a relapse. The observed smaller CSA in clubfoot and relapse patients when compared to TDC was expected given the available literature in which clubfoot patients with and without a relapse show more atrophy of the lower leg muscles when the affected side is compared to the nonaffected side [15]. This smaller CSA could indicate lower maximal plantarflexor strength. Lower plantarflexor strength has already been found in previous studies in clubfoot patients [19]. The smaller CSA combined with a shorter muscle belly is likely to result in a smaller muscle volume. This is in line with previous studies that showed a decreased muscle volume in the affected side of clubfoot patients when compared to the nonaffected side and to TDC [13,15]. We found a correlation between the smaller CSA and a lower plantarflexor moment in all clubfoot patients. The lower plantarflexor moment and ankle power observed in all clubfoot patients could therefore be affected by the smaller muscles, smaller muscle fascicles and higher pennation angle which is less optimal for dynamic force generation [16].

Moreover, a longer relative tendon with shorter muscle belly in all clubfoot patients was related to better functional gait outcomes such as higher maximum ankle power and plantarflexor moment. Typically, a longer relative tendon is expected to be related to a higher ankle power, because the muscle-tendon ratio affects the stiffness of the muscle-tendon complex which is related to the energy return capabilities [25]. A longer AT is more compliant when the material properties of the tendon do not change, and therefore more elastic recoil of the tendon could generate faster force which results in more ankle power generation [26]. Although clubfoot and relapse patients show a longer relative tendon compared to TDC, the ankle power is reduced. This means that the potentially beneficial effect of a long and more compliant tendon did not translate to better functional characteristics in clubfoot and relapse patients. As this longer relative tendon comes at the cost of a shorter muscle, it seems that differences in the plantarflexor muscles in all clubfoot patients have a larger effect on the functional outcomes in gait. Previous literature has shown that clubfoot patients have weakness of the plantarflexor muscles [19], however, as we did not measure the plantarflexor strength in our study population, we cannot draw clear conclusions in terms of plantarflexor weakness.

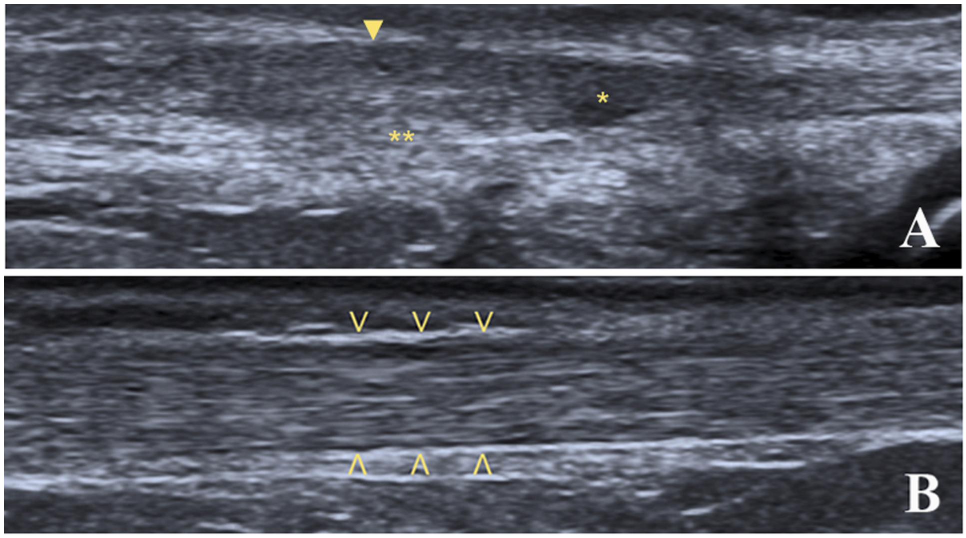

Fig. 1. Longitudinal ultrasound images of the Achilles tendon with and without irregularities. (A) Achilles tendon with irregularity; hypoechoic signal (*), focal thickening (▾) and vague lower boundary of the tendon (**). (B) Normal Achilles tendon; homogenic, parallel fibre pattern with clear boundaries (arrows) and no thickening.

Table 4
Spearman rank correlations between functional and morphological parameters for typically developing children and clubfoot patients.

	Max. dorsiflexion during walking [°]		**Max. power [W/kg]**		**Max. plantarflexor moment [Nm/kg]**	
	TDC	All clubfoot	TDC	All clubfoot	TDC	All clubfoot
Muscle-tendon ratio	0.640*	-0.204	0.277	-0.440*	-0.012	-0.310
Muscle CSA [mm]	N/A	N/A	0.005	0.330	0.412	0.640*
Pennation angle [°]	N/A	N/A	-0.027	0.368	-0.170	0.170
Fascicle length [mm]	0.238	-0.023	0.121	-0.174	0.335	0.221

* Significant correlation. TDC = typically developing children; CSA anatomical cross-sectional area; N/A = not applicable.

Another possible explanation for the finding that clubfoot and relapse patients showed lower ankle power and plantarflexor moment despite a longer relative tendon could be that there is a change in material properties of the muscle-tendon complex. Although we did not directly measure tendon elastic modulus as a material property, tendon quality was assessed This study showed that clubfoot and relapse patients had more irregularities of the AT compared to TDC. Irregularities in the tendon could indicate scarring and peritendinous adhesions which can weaken the internal tendon structure and restrict sliding of the tendon [27]. Changes within the internal structure can include changes in tendon matrix, abnormal collagen fibre orientation and formation of dense collagen type III fibres, which could result in a stiffer tendon [26]. However, irregularities of the tendon were difficult to analyse, as no objective assessment criteria are available yet and ultrasound settings were optimised manually for every patient. Therefore, interpretation of the qualitative results from this study should be done with caution.

Even though relationships were found between the muscle-tendon ratio and ankle kinetics, no relationship was found for the muscle-tendon ratio and maximum dorsiflexion during walking in all clubfoot patients. On the contrary, TDC showed a higher muscle-tendon ratio and thus a shorter relative AT to be related to a higher maximum dorsiflexion during walking. A longer relative muscle is expected to cause less resistance during the lengthening phase of the plantarflexor muscle in stance and thus result in a higher maximum dorsiflexion during walking [28]. The absence of this mechanism in clubfoot and relapse patients might also be the result of the change of material properties of the muscle-tendon complex that was previously mentioned. Furthermore, bony deformations in clubfoot and relapse patients, such as flat-top-talus, and limited passive dorsiflexion might negatively affect the maximum dorsiflexion during walking [29]. Previous literature reported a mean passive dorsiflexion of 18.9 ± 6.0° in TDC from 4 to 10 years old, which is comparable to the result of the clubfoot group [30]. However, the passive dorsiflexion of the relapse group was significantly lower when compared to the clubfoot group.

There are a few limitations to this study that must be considered. Firstly, the study groups were relatively small. To overcome this and test the reliability of the results, effect sizes were calculated. Most morphological and functional outcome measures showed large effect sizes indicating reliable results even with the small study population. However, the small group sizes might have affected the outcomes of the correlation analysis, which could explain why TDC did not show several expected relationships. Not only were the study groups relatively small, it is challenging to separate clubfoot patients into two distinct groups. Firstly because of the natural diversity in clubfoot patients itself, and secondly because clubfoot patients might develop a relapse after the measurements and thus might show different results than clubfoot patients who do not develop a relapse afterwards. Despite the fact that the separation of the groups is important considering the outcome of clubfoot treatment there are only a few studies in which a distinction between clubfoot patients is made at all. Therefore, the division that was made in this study might provide a first good overview of the muscle-tendon properties in the clubfoot population. Besides, in this study we only considered the properties of the medial gastrocnemius, which is part of a larger muscle group that contributes to the stiffness of the ankle plantarflexor complex. Information about the properties of the soleus and lateral gastrocnemius would have given a more complete overview, but given the similar function of the three muscles, it was expected that the measured adaptations in the gastrocnemius medialis reflect changes in all three muscles. Furthermore, we used 2D ultrasound images to quantify 3D structures. This could introduce projection errors and underestimation of the real fascicle length. However, the 2D method has shown good reliability [31].

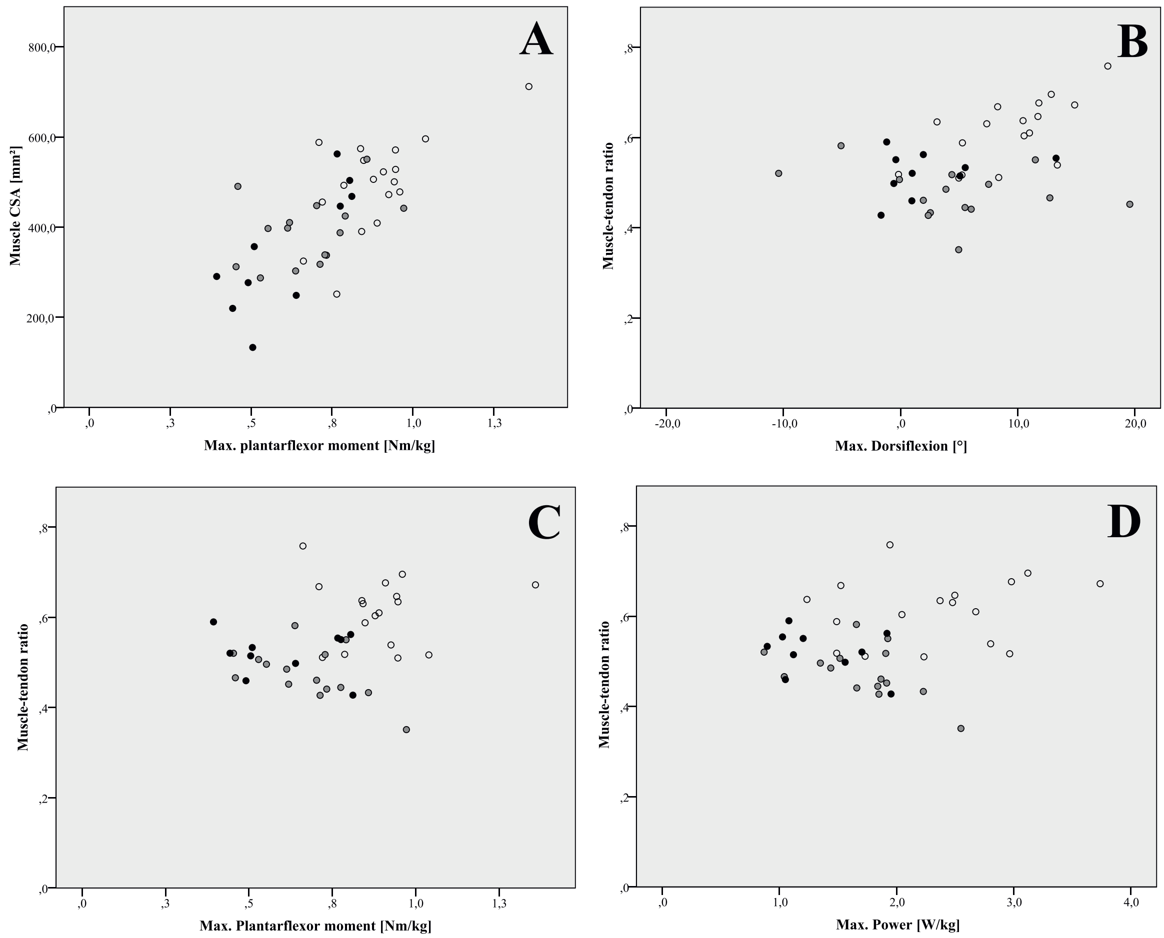

Fig. 2. Correlations between functional and morphological parameters for TDC and clubfoot patients: A maximum plantar flexor moment versus anatomical cross-sectional area; B maximum dorsiflexion during walking versus muscle-tendon ratio; C maximum plantar flexor moment versus muscle-tendon ratio; D maximum power versus muscle-tendon ratio. CSA anatomical cross-sectional area; TDC typically developing children. ∘ TDC; • Clubfoot patients; • Relapse clubfoot patients.

Despite the limitations, this is the first study to investigate morphological and functional parameters in clubfoot relapse patients. We showed altered muscle-tendon morphology and lower ankle kinetics and kinematics in clubfoot and relapse patients compared to TDC. Also, different relationships between morphology and function were found in all clubfoot patients. These findings aid understanding of problems clubfoot children may experience and future treatment planning. Future studies should focus on the material properties such as echogenicity and stiffness of the tendon which could provide additional objective information about muscle-tendon quality. Besides, it would be interesting to look at the trainability of clubfoot (relapse) patients and focus on the effect of physiotherapy on the found abnormalities in morphology and its effect on function.

CRediT authorship contribution statement

S.D.N. Wijnands: Investigation, Formal analysis, Writing – original draft. **M.C. van der Steen:** Conceptualization, Supervision, Writing – review & editing. **L. Grin:** Formal analysis, Investigation, Writing – review & editing. **L. van Oorschot:** Investigation, Writing – review & editing. **A.T. Besselaar:** Resources, Writing – review & editing. **B. Vanwanseele:** Conceptualization, Supervision, Writing – review & editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2022.01.007.

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