

Original Article

Ultrasound examination of intrinsic foot muscles in patients with 1st metatarsophalangeal joint arthrodesis^{*}

Abbis H. Jaffri^{*}, Jay Hertel, Susan Saliba

Department of Kinesiology, University of Virginia, Charlottesville, VA, United States

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ABSTRACT

1st MTP arthrodesis often alleviates pain in osteoarthritis of hallux, long term outcomes vary, yet there is little known about potentially modifiable changes in the small muscles of the foot and hallux. This study was performed to determine the changes in the size of the Intrinsic Foot Muscles (IFMs) after the arthrodesis of the 1st metatarsophalangeal (MTP) joint by comparing the cross-sectional area (CSA) and muscle thickness (MT) of Abductor Hallucis (AbH), Flexor Digitorum Brevis (FDB) and Flexor Hallucis Brevis (FHB) between surgical and non-surgical feet. A convenience sample of 18 feet of 9 subjects (age: 57.56 ± 9.07 , weight: 81.33 ± 1.32 kg, height: 163.26 ± 11.03 cm) with a unilateral history of 1st MTP arthrodesis was recruited. B-mode ultrasound images were collected during sitting and standing positions with a wireless 8-MHz transducer. Hand-held dynamometer was used to measure toe flexion strength. CSA and MT of the surgical feet were significantly lower ($P < 0.05$) for AbH and FHB in both positions. For FDB, the significant difference ($P < 0.05$) was smaller MT in standing. Significantly lower ($P < 0.05$) toe strength was observed in involved toe compared to uninvolved. Greater correlations were seen between toe strength and CSA of FHB and AbH in uninvolved toes compared with involved toes. IFMs in the surgical foot exhibited reduced CSA and MT. Weak core muscles of the foot may result in transmission of shock and forces to the foot skeleton which can lead to skeletal problems such as metatarsalgia, IP joint arthritis etc. that are seen as post-surgical complications. There is nothing in literature that delineates the rehabilitation of foot in this group of patients after surgery. This directs surgeons and clinicians to integrate IFM training in the rehabilitation programs after surgery. Developing appropriate rehabilitation protocols for these patients may help in preventions of post-surgical complications.

1. Introduction

Pain and disability associated with the toe region makes up 14% of the non-traumatic, and 21% of the traumatic consultations in the primary care setting [1]. Hallux plays an integral role in the locomotion, and is mostly involved in the toe-off phase of gait [2]. The integrity of 1st metatarsophalangeal joint (1st MTPJ) can be compromised because of bony malalignment, hallux valgus, hallux rigidus, ultimately leading to osteoarthritis (OA) of the 1st MTPJ [3,4]. Potential causes of the OA of the 1st MTPJ include overuse, trauma, prior surgeries, deformation, difference in the length of the first metatarsals [3,4]. OA of the 1st MTPJ results in chronic pain, and negatively affects the quality of life of patients [3]. Arthrodesis or the fusion of the 1st MTPJ is performed in

individuals who suffer from severe OA to relieve pain and improve quality of life [3,4]. Approximately, 80% of the patients are satisfied with the outcomes of surgery related to pain relief [3]. However, 20% of the patients remain unsatisfied with the outcome of surgery for the reasons not very well-known [3]. It has been shown that lack of motion in the 1st MTPJ after arthrodesis results in compensation by lateral toes for restoring foot function, resulting in more loading on lateral toes that may cause arthritis of lateral MTP and IP joints and may also cause metatarsalgia [3,5]. Gaudin et al. [6] reported 158 cases of revision 1st MTPJ arthrodesis, 11% of these revisions were because of IP joint disorders developed because of first surgery, 11% because of metatarsalgia, 8% because of malunion and 14% because of non-union.

Interestingly, the insult to the bones and joints of the foot seen after

Abbreviations: AbH, Abductor Hallucis; FHB, Flexor Hallucis Brevis; FDB, Flexor Digitorum Brevis; 1st MTPJ, 1st metatarsophalangeal joint; IP, interphalangeal; ND, navicular drop; SFE, short foot exercise; CSA, cross-sectional area; MT, muscle thickness; US, ultrasound; SD, standard deviation; ICC, intraclass correlation coefficient; CI, confidence interval; ES, effect size

^{*} The University of Virginia's Institutional Review Board approved this project with an IRB #20548.

^{*} Corresponding author at: Exercise and Sport Injury Laboratory, University of Virginia, 210 Emmet Street, PO Box 400407, Charlottesville, VA 22904-4407, United States.

E-mail address: ahj8uw@virginia.edu (A.H. Jaffri).

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Fig. 1. The customized step used in this study for taking US images and the sitting and the standing position during which images were taken.

1st MTPJ arthrodesis are similar to what are seen when there is weakness of the intrinsic foot muscles (IFMs), which causes greater forces on the skeleton of the foot causing foot skeleton problems such as metatarsalgia and arthritis in foot joints [7]. Many of the IFMs are inserted on the 1st MTPJ. Therefore, lack of motion after arthrodesis of 1st MTP may result in changes in the structure and function of the IFMs. Inability of the foot muscles to compensate for lack of motion or weight bearing by the 1st MTPJ may also be adding more pressure on foot skeleton and advancing the foot problems post-surgery in the patients who have poorer surgical outcomes. IFM activation results in smaller ground reaction forces and greater shock absorption during gait and hence less pressure on the foot skeleton [8].

However, the bigger challenge for clinicians and researchers is the assessment of the IFMs. Due to the multiarticular nature of the IFMs it is difficult to assess these muscles. MRI can be used as a reliable measure to assess the morphology of the IFMs but MRI is not readily available in many clinical settings [9]. Previous literature has validated ultrasound (US) imaging with MRI and has shown to have a good correlation for the quadriceps muscles [10]. US examination of the IFMs has considerably helped researchers and scientists to understand the structure and function of the IFMs that remained a challenge for a long time [11–13]. Moreover, US imaging has shown to be the only reliable method that can be used to directly visualize these muscles and differentiate them from extrinsic muscle activity [11,12]. To our knowledge, there is no study that has assessed the IFMs after 1st MTPJ arthrodesis. Therefore, the aim of this study was to assess the changes in the morphology and structure IFMs after 1st MTP arthrodesis using US imaging. We hypothesized that there will be significant changes in the size and shape of the IFMs in surgical when compared to non-surgical foot, specifically for the Hallux muscles.

2. Methods

A cross-sectional study of subjects with unilateral 1st MTPJ arthrodesis was performed, and each participant served as his own control. The independent variables were feet surgical (involved) vs non-surgical (uninvolved). The dependent variables were muscle thickness (MT) and cross-sectional area (CSA) of the IFMs; as well as the strength measures of IFMs. The muscles imaged in this study were Abductor Hallucis (AbH), Flexor Hallucis Brevis (FHB) and Flexor Digitorum Brevis (FDB).

2.1. Participants

A convenience sample 18 feet with 9 surgical and 9 controls of 6 females and 3 males were recruited for this study (months from

surgery = 29.1 ± 17.5 ; age(years) = 57.56 ± 9.07 ; height(cm) = 163.2 ± 11.03 ; weight(kg) = 81.33 ± 13.32). Inclusion criteria included: have had unilateral arthrodesis procedure to the 1st MTPJ, have had surgery at least 6 months prior to data collection, be over the age of 18 years, have no history of any other lower extremity injury/surgery in the past 6 months, be able to walk for at least 10 min, and had not been diagnosed with Diabetes Mellitus, Multiple Sclerosis, or Parkinson's disease. Potential subjects were recruited from a university health system orthopedic foot and ankle clinic staffed by three surgeons. Participants provided written informed consent prior to participation and the study methods were approved by the University of Virginia Institutional Review Board for Health Sciences Research.

3. Instruments

US imaging was performed using a Siemens Acuson Freestyle US system with a wireless 8-Mhz linear transducer (Siemens, Mountain View, CA). The images were then measured using ImageJ version 1.50f (National Institutes of Health, Bethesda, MD) loaded onto a HP windows laptop. US scanned all images at 55 dBm a 16 Hz scanning frequency and at the depth of 3.5 cm.

3.1. Testing procedure

3.1.1. Ultrasound measures

A customized step (Fig. 1) was created by investigators in the lab with an aperture of 14 cm to take IFMs images in closed chain position, sitting and standing. The US imaging was first performed in the sitting followed by bilateral standing position. The probe location proven to be reliable and valid Croft et al. [11] Angin et al. [12] and Battaglia et al. [14] was used for this study. Briefly, AbH was traced by placing the probe along a line perpendicular at the anterior aspect of the medial malleolus for CSA and was rotated to 90° for thickness measure. The CSA of FDB was identified by scanning the probe perpendicular to a line from the calcaneus to the third toe, and for thickness measure probe was rotate at 90°. For CSA of FHB, the probe was placed perpendicular to the shaft of the 1st metatarsal at the thickest portion of the muscle and then it was rotated to 90° for thickness measures.

3.1.2. Force measures

A microFET 2 Handheld Dynamometer (Hoggan, Utah) was used to assess plantarflexion peak force at the 1st MTP joint in the sitting position. Examiner had the dynamometer in their hand and made sure they had contact with the ground. Patients sat with their foot in slight dorsiflexion so that they can push down with their hallux on the dynamometer. Patients were then asked to push down only through their

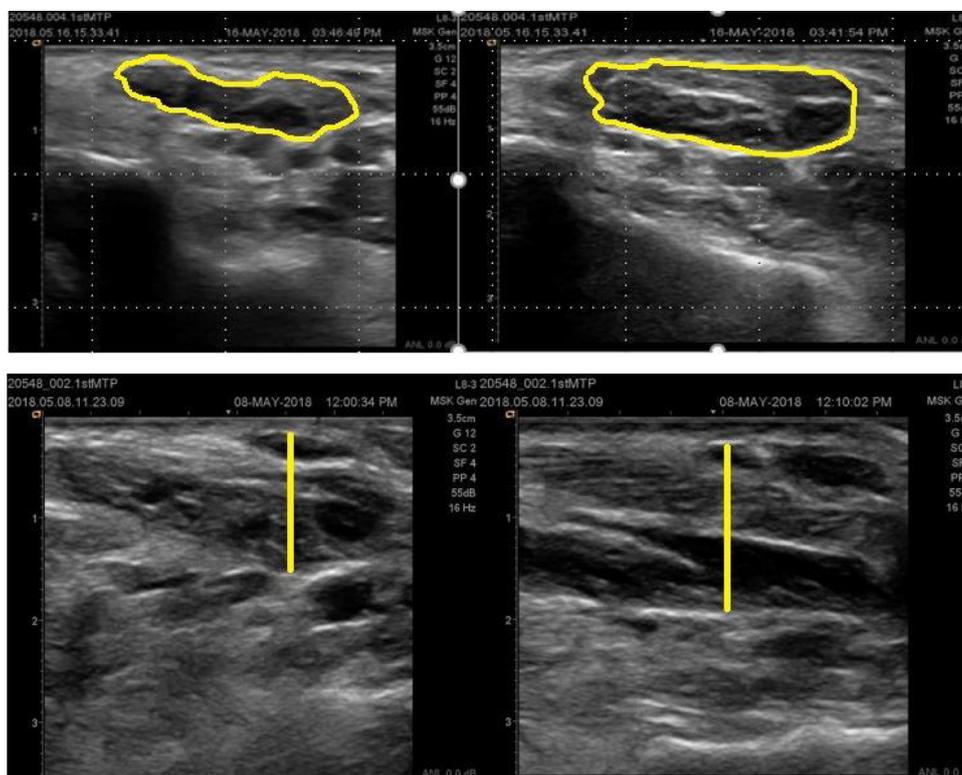


Fig. 2. Measured Ultrasound Images of Abductor Hallucis CSA and MT in sitting position. The top images are measured CSA and the bottom are measured MT. Left side images are for the surgical toe and the right sided images are for the non-surgical toe.

hallux while examiner supported the dynamometer through their hand. Handheld dynamometry has shown to be a reliable method for measuring toe flexion strength [15].

3.2. Data processing

After the data collection, the images were exported using a flash drive and uploaded to a laptop for image measurement using ImageJ. The CSA images were measured by marking the internal circumference of the fascial border of each muscle. The MT was taken with a linear measurement of the thickest part of the muscle. Measured US images are shown in (Fig. 2) for AbH in the sitting position are provided as an example. Similar methods were used to measure FHB and FDB in sitting as well as standing position.

Once all the measurements were taken, averages were calculated for each measurement type of each position and image view for each participant. Although all the images were taken by the same investigator. Excellent intra-observer reliability (ICC > 0.90) was found for the images taken (Table 1 for specific values). The potential for the recall bias was controlled by blinding the examiner to the results of each measurement.

3.3. Data analysis

The statistical analysis was performed using Minitab for Windows (Minitab Inc. State College, PA) with an α error of 0.05 (95% CI), and a desired power of 80% (β error of 0.2). Data was assessed for normality using Shapiro–Wilk Test ($P > 0.05$) for the dependent variables. Paired t-test was used to assess the differences between the involved and the non-uninvolved feet for CSA and MT of the AbH, FDB, and FHB for both in sitting and the standing positions. Paired t-test was used to assess the differences between the plantar flexor force measures between involved and uninvolved toe. Cohen’s *d* effect sizes were performed in order to determine the magnitude of difference between

Table 1

Intraclass correlation (ICC) representing intra-observer reliability between the three consecutive images taken.

	ICC
AbH CSA	0.99
AbH MT	0.99
FDB CSA	0.99
FDB MT	0.98
FHB CSA	0.99
FHB MT	0.97

Values range from 0 to 1.

AbH CSA = abductor hallucis cross-sectional area; AbH MT = abductor hallucis muscle thickness; FDB CSA = flexor digitorum brevis cross-sectional area; FDB MT = flexor digitorum brevis muscle thickness; FHB CSA = flexor hallucis brevis cross-sectional area; FHB MT = flexor hallucis brevis muscle thickness.

fused and normal feet for the CSA and MT of the IFMs. Effect sizes were interpreted as follows: < 0.2 is trivial; 0.2–0.4 small ; 0.5–0.7 moderate; ≥ 0.8 large [16].

Pearson correlational analysis was used to evaluate the relationship between the CSA of the AbH and the FHB with the force produced using hand-held dynamometry.

4. Results

The (mean (SD)) of the three images taken in each position in both CSA and MT views were taken.

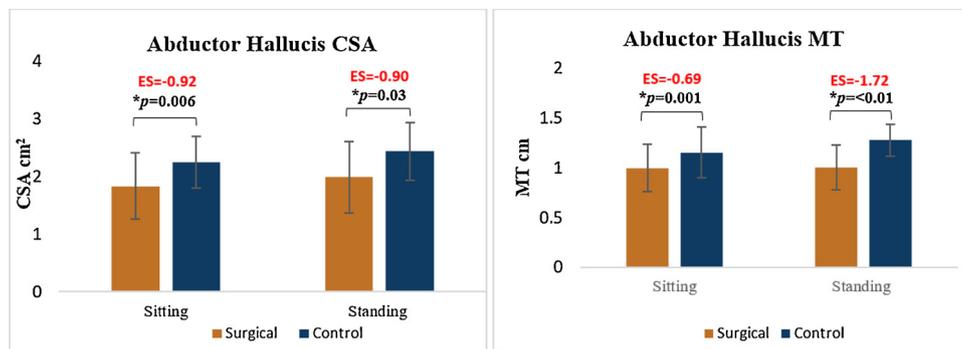


Fig. 3. Bar graphs for CSA and MT of Abductor Hallucis. Mean ± SD of abductor hallucis muscle cross-sectional area (CSA) and muscle thickness (MT) for surgical (involved) and control (uninvolved) foot in sitting and standing position. Significance P = 0.05. ES = effect size.

4.1. Abductor Hallucis

CSA of the AbH for the involved foot in both sitting (1.83 cm² (0.58)) and standing (1.98 cm² (0.61)) was significantly smaller than the uninvolved foot in sitting (2.25 cm² (0.45)) as well as standing (2.43 cm² (0.49)) (Fig. 3). Smaller MT for the involved foot was found in sitting (0.99 cm (0.237)) and standing (1.00 cm (0.23)) as compared to the uninvolved foot in both sitting (1.158 cm (0.24)) and standing (1.27 cm (0.16)) (Fig. 3).

4.2. Flexor Hallucis Brevis

Significantly smaller CSA of FHB was found in involved foot in sitting (1.16 cm² (0.57)) and standing (1.27 cm² (0.70)) when compared to uninvolved foot in sitting (1.55 cm² (0.56)) and standing (1.58 cm² (0.57)) (Fig. 4). Likewise, significantly smaller FHB MT was found in sitting (1.05 cm (0.21)) as well as standing (1.04 cm (0.25)) as compared to sitting (1.26 cm (0.24)) and standing (1.28 cm (0.21)) on the uninvolved side (Fig. 4).

4.3. Flexor Digitorum Brevis

No statistically significant differences between the involved (1.60 cm² (0.915)) and uninvolved (2.02 cm² (0.78)) in the CSA of FDB in the sitting position as well as no differences were found in the involved (1.85 cm² (0.93)) and uninvolved (2.18 cm² (0.83)) in the standing position (Fig. 5). However, we did find statistically significant smaller MT on the involved (0.89 cm (0.24)) side compared to uninvolved (1.08 cm (0.27)) foot for MT in sitting. In standing position, no differences were seen between the involved (0.93 cm (0.30)) and uninvolved (1.05 cm (0.19)) in the MT (Fig. 5).

4.4. Toe dynamometry

Force (Newton) produced by the involved toe (15 ± 12.62) was significantly (P = 0.02) lower than the force produced by the uninvolved toe (20.12 ± 12.67). Stronger correlations of 0.57 and 0.65 were observed between CSA and force measures of the uninvolved toes for both AbH and FHB, respectively. However, involve toes showed weak correlations of 0.35 and 0.22 between CSA and force measures for AbH and FHB, respectively.

5. Discussion

This is the first study aimed at studying plantar foot musculature after 1st MTPJ arthrodesis. This is also the first time that IFMs are assessed in any pathological or surgical population in the weight-bearing position. Weight-bearing is a functional position of these muscles as they get activated when the bear load in our daily living activities [14]. Our results indicated that there was a significant decrease in the size of the IFMs with large effect sizes between involved and uninvolved toes (Figs. 2–5). The results of this study show significant atrophy in the surgical foot compared with the non-surgical. Force dynamometry also showed that there was lower force produced by the involved toe when compared with uninvolved. Another interesting finding was greater association between CSA and force produced by the hallux for both AbH and FHB on the uninvolved toe when compared with the involved toe.

Changes in muscle morphology can be expected in the arthrodesis of any joints. However, the changes in the IFMs observed in the current study cannot be just attributed to the lack of motion in the 1st MTP joint post-surgery. IFMs are unique in terms of their function, IFMs are multi-joint muscles with a primarily eccentric action to resist the load of the body during functional activities with minimal movements in the metatarsophalangeal joints [17]. Intuitively, even when there is fixation of the 1st MTP joint the IFMs of the hallux can still activate and function

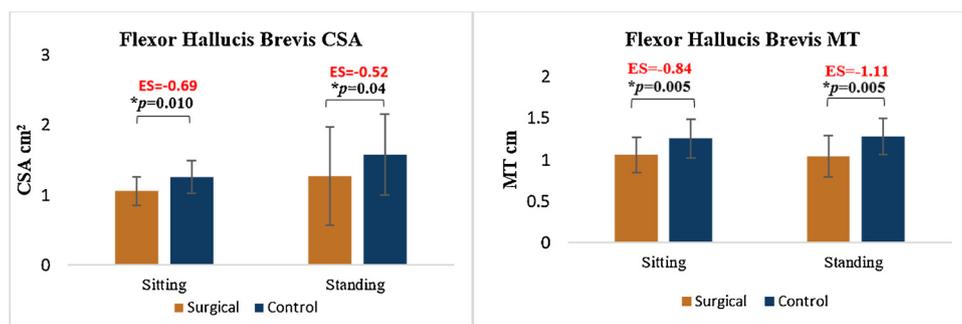


Fig. 4. Bar graphs showing CSA and MT for Flexor Hallucis Brevis. Mean ± SD of Flexor Hallucis Brevis muscle cross-sectional area (CSA) and muscle thickness (MT) for surgical (involved) and control (uninvolved) foot in sitting and standing position. Significance P = 0.05. ES = effect size.

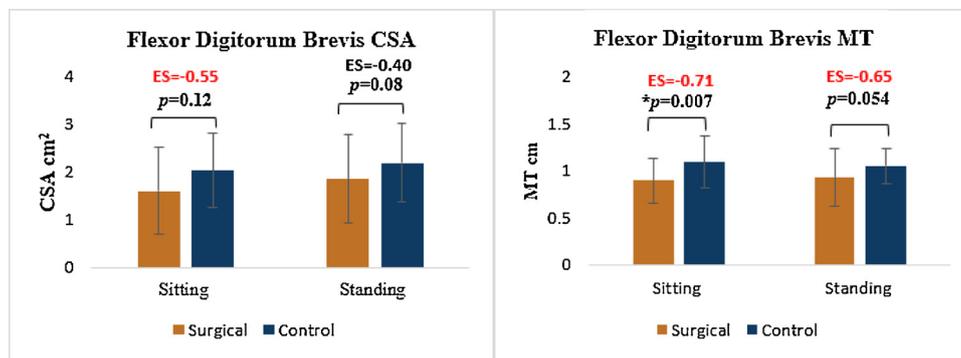


Fig. 5. Bar graphs showing CSA and MT of the Flexor Digitorum Brevis. Mean \pm SD of Flexor Digitorum Brevis muscle cross-sectional area (CSA) and muscle thickness (MT) for surgical (involved) and control (uninvolved) foot in sitting and standing position. Significance $P = 0.05$. ES = effect size.

with the increase in the load on the foot. [18]. Kelly et al. [18] demonstrated that activation of the IFMs increased loading of the longitudinal arch to 125% of the body weight resulted in proportional activation of the IFMs in the sitting position without any movement in the metatarsophalangeal joints. In this study, it was found that even in weight-bearing (functional) position, the IFMs in the involved foot were smaller in size when compared with the uninvolved toe showing an inability to sustain loads. Transfer of forces to the skeleton of the foot due to the weak foot muscles can result in structural attenuations of the foot skeleton and patients can develop foot skeletal problems such as metatarsalgia, IP joint arthritis etc. [7,19]. Previous studies have suggested that there is a 30% increase in plantar loading because of weakness of the IFMs causing more pressure on the foot skeleton [7,19].

Interestingly, it was also found an uniform decrease in the size (moderate to large effect sizes) of the FDB muscles (Fig. 3) on the involved foot when compared to uninvolved, although there was no fixation for the lateral metatarsophalangeal joints where FDB inserts. FDB is the largest of all the plantar intrinsic foot muscles [17]. The atrophy in FDB provides a potential explanation for the lateral IP joint arthritis and metatarsalgia that some of the patients with 1st MTP joint arthrodesis are developing after surgery. Weaker FDB may result in smaller absorption of the forces and greater pressure on the lateral IP joints leading to destructive changes in the joints resulting in lateral IP joints arthritis. Patients developed weakness in the surgical toe perhaps due to decrease in loading on the surgical toe after arthrodesis.

The literature regarding the structure and function of IFMs is somewhat limited but is evolving. Traditionally, it was thought that IFMs are small muscles with limited function, and the ability to clinically discern strength is difficult. However, it has been shown that IFMs are even bigger than some extrinsic leg muscles in healthy individuals [19,20]. Total IFMs volume (113.3 cm^3) was greater than flexor hallucis longus (74.0 cm^3), flexor digitorum longus (18.7 cm^3) and Tibialis posterior (104.2 cm^3) substantiating their functional importance [19,20]. Many of these plantar IFMs have their insertions on the 1st MTPJ. The weakness of the IFMs noted in this study can also have functional implications as IFMs are shown to have an integral role in functional activities such as walking and running [21], balance [22] and prevention of falls [23] in older adults.

Strengthening the IFMs could help these patients increase tissue capacity to sustain mechanical load, thus may improve long term outcomes. There are no studies in the literature that have focused on the rehabilitation programs after 1st MTPJ arthrodesis. This study serves as the first step in identifying the weakness of the IFMs and providing a potential explanation of the unwanted outcomes seen in some patients after surgery. Future studies should focus on rehabilitation of the IFMs in this group of patients to see if the rehabilitation can improve functional outcomes after surgery.

6. Limitations

This study is an important addition to present body of literature as this is the first attempt made to assess the IFMs after 1st MTP joint arthrodesis. Therefore, there was no prior study on which we could have powered this study consequently one limitation was small sample size. However, a post-hoc sample size analysis using the CSA of the AbH revealed that the study was appropriately powered (sample size of 7 feet needed in each group with standard deviation of 0.49, effect size of 1.7 and minimum difference of 0.83). IFM assessment should be an important consideration in these patients because 1st MTPJ forms the insertion point for many of the IFM muscles. However, there were some limitations. There was no control group of healthy subjects present in the experimental design. Hence the study focussed on patients with unilateral 1st MTPJ so that patient's non-surgical foot can serve as a control. The benefit of such study design is that there is less inter-subject variability. Another limitation of this study is inability to assess these patients pre-operatively. As such, only subjects who already had gone through the procedure of 1st MTPJ arthrodesis were included so the design was retrospective in nature which makes it hard for us to distinctly assert that the atrophy of the IFMs happened only after surgery.

7. Conclusion

In conclusion, distinct atrophy was seen in patients with 1st MTP arthrodesis. There was greater correlation of toe flexion strength with the CSA found in the non-surgical toe compared with the surgical toe. This shows that in surgical toe there was no activation of the IFMs.

Brief summary

What is already known:

- Patients undergone arthrodesis of 1st MTP suffer from foot related problems post-surgery.
- Complications developed in these patients are similar to what are seen after intrinsic muscles weakness.
- Revision surgery is needed when these problems exacerbate.

What this study adds:

- There is an atrophy of intrinsic foot muscles in 1st MTP arthrodesis patients.
- The atrophy of intrinsic muscles provides an explanation of the complications developed after surgery.
- This study establishes the need of rehabilitation in these patients.

Competing interests

The author declare they have no competing interests.

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