Heliyon 9 (2023) e18252

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Current evidence regarding 2D ultrasonography monitoring of intrinsic foot muscle properties: A systematic review

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ARTICLE INFO

Keywords:
Intrinsic foot muscles
Reference values
Reliability
Systematic review
Ultrasound imaging

ABSTRACT

Background: Ultrasonography can discriminate between intrinsic and extrinsic foot muscle properties and has therefore gained considerable popularity as an indirect strength evaluation. However, an overview on the use of ultrasound for assessing intrinsic foot musculature (IFM) is currently lacking.
Research question: What is the current evidence regarding (1) 2D ultrasonography protocols and its reliability? (2) Reference values for cross-sectional area and dorso-plantar thickness evaluation in asymptomatic and symptomatic persons?
Methods: The PRISMA guidelines were used to conduct this systematic review. Eight databases (PubMed, Embase, Web of Science, Cochrane Library, Scopus, CINAHL, SPORTDiscus and EuropePMC) were searched up to November 1, 2021. Studies reporting quantitative 2D ultrasound findings of the intrinsic foot muscles with no limitation to sex, BMI, ethnicity or physical activity were included. Studies were assessed for methodological quality using the Downs and Black checklist.
Results: Fifty-three studies were retained. Protocols showed an overall good to great reliability, suggesting limits of agreement between 8 and 30% of relative muscle size with minimal detectable changes varying from 0.10 to 0.29 cm^2 for cross-sectional area and 0.03–0.23 cm for thickness. Reference values are proposed for both cross-sectional area and thickness measurements of the abductor hallucis, flexor digitorum brevis, flexor hallucis brevis and quadratus plantae in asymptomatic persons. This could not be performed in the symptomatic studies due to a limited number of relevant studies addressing the symptomatic population, therefore a clinical overview is outlined. Clinically, IFM properties have been studied in ten distinct pathological conditions, predominantly pointing towards decreased muscle properties of the abductor hallucis.
Significance: We provide a clear and comprehensive overview of the literature regarding 2D ultrasonography of the IFM, making the available evidence more accessible to decision makers and researchers.

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https://doi.org/10.1016/j.heliyon.2023.e18252
Received 21 June 2023; Received in revised form 10 July 2023; Accepted 12 July 2023
Available online 17 July 2023
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1. Introduction

The intrinsic foot muscles (IFM) play an important role in sports activities as they contribute to the elastic energy absorption and generation of the medial longitudinal arch while working in conjunction with the plantar aponeurosis, ligaments and extrinsic foot muscles [1–4]. According to the 'foot core' paradigm, proposed by McKeon and colleagues, the IFM act as principal local stabilizers of the foot arches in a similar way the deep trunk muscles do in stabilizing the vertebral segments [5]. They contribute to balance performance and contract eccentrically during the early stance phase of rearfoot running and shorten during the late stance phase to produce positive work [2]. There is increasing evidence towards an association of IFM weakness and atrophy across the clinical course of a number of musculoskeletal conditions, including plantar fasciitis [6], posteromedial shin pain [7] and chronic ankle instability [7–11], and systemic diseases, such as diabetic mellitus [12]. IFM strengthening has therefore been recommended as an integral part of foot and lower limb rehabilitation programs [9,13,14] as well as sport-specific strength training and prevention exercises [15].

In order to assess IFM strength or their response to training, a valid and reliable strength evaluation is required. However, intrinsic and extrinsic foot muscles share similar functions, which makes a clinical differentiation among both muscle groups very challenging [16]. Currently, clinicians rely on direct and indirect methods. Direct methods include clinical tests such as the paper grip test [17] or dynamometry [18] but these evaluate several muscles at a time, not allowing the clinician to assess a single intrinsic foot muscle. Indirect methods commonly use medical imaging to quantify individual muscle size. As a muscle's cross-sectional area (CSA) and force production are strongly correlated, the CSA can be used to estimate muscle strength [19,20].

Magnetic resonance imaging (MRI) is considered the method of choice, but MRI is neither cost-effective nor feasible for daily clinical practice. Ultrasonography (US) may provide a more clinical friendly and portable alternative [21]. However, ultrasound imaging is highly dependent on the sonographer's level of technical skill and professional background. Furthermore, patient position, probe location and gain, depth or frequency settings may influence image capturing [22–24]. Medical and paramedical staff should be informed about this diversity in protocols when choosing the most appropriate one for a given specific objective. Determining reliability and repeatability is therefore highly relevant since it provides the basis for establishing reference values.

This systematic review aims to (1) provide an overview of 2-dimensional morphology-oriented ultrasound evaluation (2D-MOUSE) protocols and their reliability and repeatability; and (2) put forward reference values concerning cross-sectional area and dorsoplantar thickness of the abductor hallucis, flexor digitorum brevis, flexor hallucis brevis and quadratus plantae.

2. Methods

This systematic review was written according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) checklist [25] and followed the methods of the Cochrane Handbook for Systematic Reviews of Interventions [26] where appropriate. The protocol was prospectively registered in the PROSPERO database (CRD42021286578).

2.1. Search strategy

The literature search was conducted during the first half of November 2021. An experienced biomedical research librarian aided in developing a sensitive search strategy. Eight different electronic databases were used: PubMed, Embase, Web of Science Core Collection, Cochrane Library, Scopus, CINAHL, SPORTdiscus and EuropePMC. Search terms were related to "ultrasonography" and "intrinsic foot muscles" and their synonyms. Search equations are provided in **Appendix 1**. Reference lists of each included study and similar reviews were screened for additional papers.

2.2. Study selection

In order to perform this systematic review, the literature search was performed using the PICO method [27]. The following inclusion criteria were set for approaching the problem:

- Population - Adults, aged 18–65 years [28], symptomatic or asymptomatic persons with no limitation to sex, BMI, ethnicity or physical activity.
- Intervention - Protocols using 2D morphology-oriented ultrasound evaluation (2D-MOUSE) of the intrinsic foot muscles.
- Comparison – None.
- Outcome measures – 2D morphology measures of intrinsic foot muscles: cross-sectional area and dorso-plantar thickness, as determined by B-mode ultrasound.

Papers were excluded for the following reasons: 1) publication type: opinion, report, meeting summary, symposium summary, letters to the editor, commentaries, guidelines, editorials, abstracts 2) exclusive use of following ultrasound modalities: three-dimensional, Doppler, elastography, ultrasound palpation, M-mode or therapeutic ultrasound 3) population: <18 or >65 years and 4) language: other than English.

The search results were imported in EndNote Library, where a deduplication process was performed following Bramer et al. [29]. After this process, the eligible papers were exported to Rayyan [30], an online collaborative tool to review papers. Blinded for each other's decisions, the eligibility assessment was performed by two reviewers (NH and JLPD) during the month of November 2021.

After each reviewer completed their selection, blinding was turned off. Conflicted papers were resolved through consensus. If not, a third reviewer (KD) made a final decision.

2.3. Methodological quality assessment

The Downs and Black Checklist [31] was used to assess the methodological quality of the non-interventional studies, this was done independently by two reviewers (NH, JLPD) [31]. It addresses completeness of reporting (ten items), external validity (three items), internal validity (thirteen items) and power (one item). For single group studies, items 5, 21 and 22 do not apply. Item 27, regarding the power of the study, was transformed into a dichotomous scale indicating whether or not a sample size calculation was reported. Nine items are not applicable for the assessment of intervention studies (items 4, 8, 13, 14, 17, 19, 23, 24 and 26). To allow comparison between the categories of studies and adjusting for the varying total items scored, the results are expressed as percentage scores. Percentage scores of >75% are considered strong methodological quality, a score of 50–74% is considered moderate, a score between 25 and 49% is considered limited and a score <25% is considered poor [9].

Quality assessment was performed to provide an overview, not to in- or exclude. In case of continued disagreement, a third reviewer was available for arbitration (KD).

2.4. Data extraction

The following data of each study were extracted independently by two reviewers (NH and JLPD) in a self-made data extraction sheet in Excel: participant characteristics, cross-sectional area and thickness of the abductor hallucis (ABH), flexor digitorum brevis (FDB), abductor digiti minimi (ADM), flexor hallucis brevis (FHB), quadratus plantae (QP), adductor hallucis (ADH), lumbricals (LUM), extensor digitorum brevis (EDB) and muscles of the first interstitial space (MIL). In addition, the reliability properties of every 2D MOUSE protocol were included in the data extraction sheet; limits of agreement (LoA), standard error of the mean (SEM), minimal detectable change (MDC) and intra-class correlation coefficients (ICC). We decided to use the following qualitative benchmarks: ICC values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively [32]. Extraction sheet is available in **Appendix 2**.

2.5. Data synthesis

We pooled the morphology measures from asymptomatic persons for the most commonly scanned muscles: Abductor Hallucis

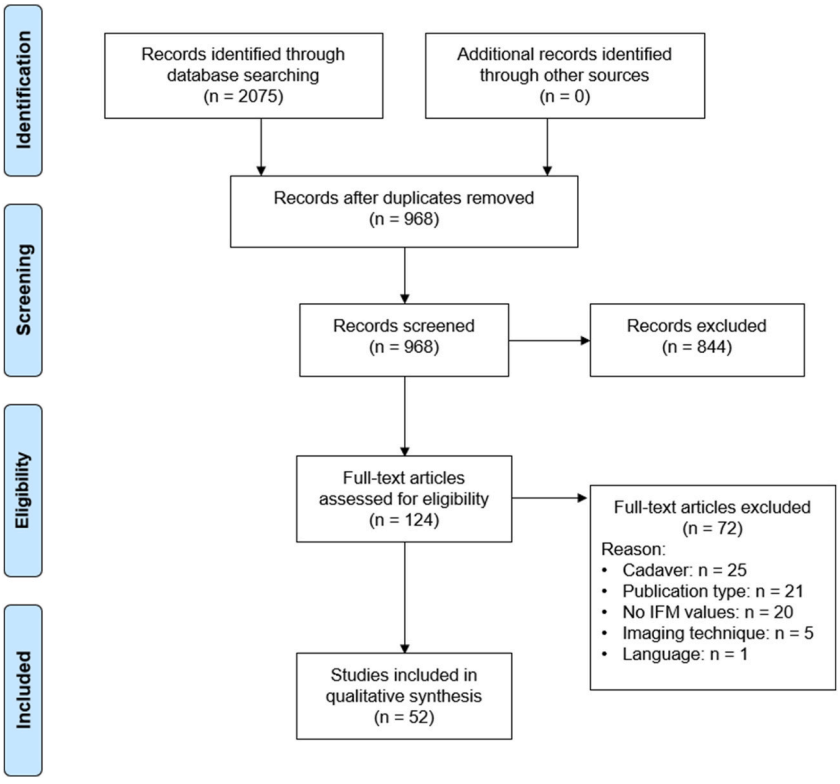


Fig. 1. PRISMA flowchart illustrating the process for the selection of the included articles for the systematic review.

(ABH), Flexor Digitorum Brevis (FDB), Flexor Hallucis Brevis (FHB) and Quadratus Plantae (QP). Descriptive statistics were calculated based on the extraction sheet provided in **Appendix 2** and expressed as the pooled mean ± two standard deviations to obtain a set of reference values for the CSA and thickness of the ABH, FDB, FHB and QP. We used the means from (i) asymptomatic studies, (ii) control groups from symptomatic studies and (iii) baseline measurements from intervention studies involving asymptomatic persons. If a study did not provide a single mean (e.g. a study where means of both the right and left foot of the same individual were provided), an author-based mean calculation was performed, as indicated by an asterisk (*).

Table 1
Characteristics of studies involving only asymptomatic participants.

Study with Downs & Black score		Participants				2D-MOUSE	
		Activity level	Sex (M/F)	Age (yrs)	BMI (*) (kg/m^2)	Muscle	Outcome measure
Abe et al., 2016 [41]	57%	Sports activity min. 2/week: judo, resistance exercise, soccer, running, canoeing (n = 34)	17/17	24 (4)	22.6 (3.4)	ABH, FDB	CSA
Abraham et al., 2020 (a) [34]	71%	UTD (n = 65)	24/41	21–82	UTD	ABH, ADM, EDB	Thickness
Battaglia et al., 2016	64%	UTD (n	9/17	25.5 (3.8)	28* (7.8)	ABH, FDB, QP	CSA, Thickness
Cameron et al., 2008 [42]	64%	UTD (n = 30)	10/20	28.2 (10.2)	23.5*	ABH	CSA, thickness
Croft et al., 2014 [23]	64%	UTD (n = 10)	4/6	29.1 (7.2)	25.5 (4.8)	ABH, FDB	CSA & Thickness
Frannetovich Smith et al., 2019 [43]	71%	UTD (n = 24)	(–)	31 (9)	24.8 (3.2)	ABH, FIS	CSA & Thickness
Fraser et al., 2018 [44]	57%	Recreationally active, measured with Godin Leisure Time Questionnaire (n = 24)	12/12	21.5 (4.8)	23.5 (2.9)	ABH, FDB, FHB, QP	CSA & Thickness
Hing et al., 2009 [45]	64%	UTD (n = 30)	10/20	28.2 (10.2)	23.5*	ABH	CSA, Thickness
Johnson et al., 2020 [46]	57%	UTD (n = 12)	8/4	23.5 (1.9)	22.7*	ABH, FDB, FHB, QP	CSA: ABH, FDB, QP Thickness: FHB
Koyama et al., 2019 [39]	76%	Elite judo athletes, holding a black belt for >6 years (n = 24)	24/0	19.8 (1.3)	25.5 (2.1)	ABH, FDB, FHB, QP	Thickness
		Control, physically active: 2h per session, >2/week (n = 24)	24/0	20.2 (1.7)	23.7 (2.6)		
Latey et al., 2018 [22]	79%	UTD (n = 21)	6/15	39.5 (10)	23.8 (3.3)	ABH, FHB	CSA
Maeda et al., 2021 [47]	79%	At least 150 min of moderate activity per week for at least 6 months (n = 27)	27	21.9 (1.9)	21.7 (2.3)	ABH, FDB, FHB	CSA & Thickness
Mickle et al., 2013 [24]	64%	UTD (n = 10)	5/5	32.1 (10.1)	UTD	ABH, FDB, FHB, ADM, QP	CSA & Thickness
Mickle et al., 2016 [48]	72%	UTD (n = 41)	19/22	28.8 (8.2)	26.0 (4.1)	ABH, FDB, FHB, ADM, QP	CSA & Thickness
Morikawa et al., 2021 [36]	71%	At least 150 min of moderate activity for at least 6 months (n = 23)	UTD	23.3 (1.9)	20.7 (2.2)	ABH, FDB, FHB	CSA & Thickness
Seok et al., 2016 [33]	79%	UTD (n = 80)	40/40	39.5 (11)	22.5 (2.3)	ABH, EDB	Thickness
Tanaka et al., 2019 [40]	59%	Well-trained sprinters, sprint training minimum 5/week (n = 26)	26/0	21.1 (2.1)	21.7*	ABH, FDB, FHB	Thickness
		Non-sprinters, recreationally active (n = 26)	26/0	21.9 (1.4)	22.2*		
Taş et al., 2019 (a) [49]	64%	UTD (n = 41)	0/41	26.9 (3.73)	21.9 (2.9)	ABH, FDB, FHB	CSA & Thickness
Taş et al., 2020 [50]	79%	Sedentary, no exercise in last 6 months (n = 40)	0/40	26.2 (5.1)	21.3 (2.2)	ABH, FDB, FHB	CSA & Thickness
Verhulst et al., 2011 [51]	71%	UTD (n = 60)	(–)	(–)	(–)	ABH, FDB	Thickness
Zhang et al., 2017 (a) [52]	57%	Recreational runners, min 10 km/week (n = 28)	18/13	25.6 (6)	21.8 (6)	ABH, FDB, QP	CSA: ABH, FDB Thickness: ABH, FDB, QP

Abbreviations: M = male, F = female, yrs = years, kg = kilograms, m = metres, UTD = unable to determine, IFM = intrinsic foot muscles, ABH = abductor hallucis, FDB = flexor digitorum brevis, FHB = flexor hallucis brevis, QP = quadratus plantae, EDB = extensor digitorum brevis, FIS = first interstitial space, * = author-based calculation of BMI.

Table 2
Characteristics of studies involving symptomatic subjects or subjects with a different foot posture.

Study with Downs & Black score		Participants				
		Characteristics	Sex (M/F)	Age (yrs)	BMI (*) (kg/m^2)	Significant differences ($p < 0.05$)
						Mean (±SD)
Abraham et al., 2020 (b) [53]	76%	SMA patients (n = 31)	13/18	32 (24–42)	23.8 (21.9, 28.9)	FDI: 0.66 (0.52, 0.78) ADM: 0.67 (0.56, 0.82) ABH: 0.99 (0.81, 1.13) EDB: 0.59 (0.41, 0.70)
		ALS patients (n = 91)	51/40			
		Asymptomatic (n = 59)	16/35	66 (54–72)	24.2 (21.8, 27.3)	FDI: 0.79 (0.57, 0.97) ADM: 0.84 (0.70, 0.98) ABH: 0.98 (0.87, 1.08) EDB: 0.50 (0.29, 0.66)
				46 (31–60)	23.5 (21.6, 28.2)	FDI: 1.10 (0.99, 1.26) ADM: 0.97 (0.85, 1.07) ABH: 1.17 (1.03, 1.34) EDB: 0.74 (0.67, 0.86)
Aiyer et al., 2015 [54]	82%	HV 20–44 yrs (n = 21)	7/14	26.0 (5.9)	24.5 (3.3)	ABH CSA: 3.53 (6.71) Th: 1.38 (0.21)
		HV 45–64 yrs (n = 17)	1/16		27.0 (5.4)	ABH CSA: 3.16 (6.88) Th: 1.24 (0.21)
		HV 65+ yrs (n = 21)	2/19	54.2 (4.8)	28.4 (8.1)	ABH CSA: 2.89 (9.73) Th: 1.19 (0.23)
				76.4 (10.1)		
Calvo Lobo et al., 2016 [55]	84%	HV (n = 20)	4/16	46.2 (11.3)	24.7 (3.38)	ABH CSA: 2.22 (0.49) Th: 0.91 (0.23); FHB CSA: 1.57 (0.41) Th: 0.93 (0.14)
		Control (n = 20)	2/18		22.9 (3.50)	
				42.1 (12.2)		ABH CSA: 2.74 (0.64) Th: 1.10 (0.26); FHB CSA: 2.13 (0.65) Th: 1.09 (0.18)
Stewart et al., 2013 [56]	79%	HV grade 1–3 (n = 64)	52/12	60.3 (20.5)	26.3 (5.2)	ABH CSA grade 1: 3.0 (0.46) grade 3: 2.73 (0.62) ABH Th grade 2: 1.14 (0.16) grade 3: 1.13 (0.17)
		Control (n = 64)				ABH CSA: 3.39 (0.56) Th: 1.33 (0.2)
Taş et al., 2019 (c) [57]	61%	HV (n = 30)	3/27	36.5 (12.4)	23.5 (3.2)	ABH CSA: 2.1 (0.3) Th: 0.97 (0.21); FHB CSA: 2.3 (0.4) Th: 1.4 (0.14); FDB CSA: 2.1 (0.4) Th: 0.97 (0.12)
		Control (n = 30)			24.0 (3.3)	ABH CSA: 2.4 (0.5) Th: 1.14 (0.22); FHB CSA: 2.7 (0.5) Th: 1.65 (0.20); FDB CSA: 1.9 (0.6) Th: 0.89 (0.18)
				36.5 (10.5)		
Angin et al., 2014 [58]	71%	Pes planus (n = 49)	29/20	24.1 (5.5)	23.8 (3.8)	ABH CSA: 2.36 ± 0.47 Th: 1.18 ± 0.11; FHB CSA: 2.66 ± 0.48 Th: 1.30 ± 0.18
		Control (n = 49)	29/20		23.2 (3.4)	
				23.4 (4.2)		ABH CSA: 2.75 ± 0.35 Th: 1.27 ± 0.10; FHB CSA: 2.97 ± 0.47 Th: 1.43 ± 0.21
Angin et al., 2018 [59]	71%	Pes planus (n = 43)	25/18	23.7 (4.8)	23.3 (3.2)	(−)
		Control (n = 68)	36/32		23.6 (3.6)	
				24.7 (6.3)		
Okamura et al., 2021 [60]	78%	Pronators (n = 13)	4/9	20.5 (1.7)	20.4 (1.5)	(−)
		Overpronators (n = 13)	4/9		20.4 (1.7)	
				20.5 (1.7)		
Sakamoto et al., 2020 [61]	61%	Flat foot (n = 43)	25/18	21.7 (3.2)	21.2*	ABH CSA: 2.36 ± 0.51 Th: 1.28 ± 0.19; ADM CSA: 0.95 ± 0.25 Th: 0.66 ± 0.11
		Typical feet (n = 34)	14/17		21.2*	
				20.9 (0.4)		ABH CSA: 2.14 ± 0.64 Th: 1.12 ± 0.19; ADM CSA: 1.15 ± 0.33 Th: 0.82 ± 0.11
Taş et al., 2018 [62]	78%	Flat foot (n = 40)	20/60	26 (21–33)	23 (20–25)	ABH Th: 1.22 (1.07–1.34)
		Control (n = 40)			22 (21–25)	ABH Th: 0.99 (0.89–1.10)
				27 (22–37)		
Zhang et al., 2017 (b) [63]	67%	Asx overpronators (n = 9)	15/11	22.6 (1.9)	21.8 (1.7)	ABH Th: 1.29 (0.08); ADM CSA: 1.89 (0.18) Th: 0.93 (0.06); FDB CSA: 2.55 (0.35)
		Normal posture (n = 17)			21.8 (2.6)	
				25.9 (6.4)		ABH Th: 1.20 (0.12); ADM CSA: 2.11 (0.21) Th: 1.06 (0.08); FDB CSA: 2.15 (0.41)
Zhang et al., 2019 [64]	61%	Sx pronators (n = 15)	9/6	23.3 (5.1)	22.6 (1.6)	ABH CSA: 2.28 ± 0.48 Th: 1.10 ± 0.13
		Asx pronators (n = 15)	10/5		22.7 (1.9)	ABH CSA: 2.71 ± 0.35 Th: 1.25 ± 0.07
				25 (5.3)		
Henderson et al., 2020 [38]	83%	DM + NP (n = 15)	15/0	61.4 (12.4)	33*	ABH CSA: 1.40 ± 0.76; FDB CSA: 1.42 ± 0.47; QP CSA: 1.16 ± 0.30; FHB Th: 1.36 ± 0.18
		Control (n = 15)	15/0		29.6*	
				61.6 (9.7)		ABH CSA: 1.96 ± 0.47; FDB CSA: 2.16 ± 0.35; QP CSA: 1.72 ± 0.71; FHB Th: 1.57 ± 0.21
Kumar et al., 2015 [65]	65%	DM + PN (n = 30)	13/5	56.2 (6.6)	23.6 (2.7)	EDB CSA: 1.72 ± 0.42; LUM1 Th: 1.29 ± 0.44; INT1 Th: 1.29 ± 0.45
		Control (n = 30)	17/13		24.6 (1.7)	
				54.4 (9.8)		EDB CSA: 2.17 ± 0.42; LUM1 Th: 1.57 ± 0.50; INT1 Th: 1.57 ± 0.50
Severinsen et al., 2007 [66]	72%	DM (n = 26)	16/10	50 (26–64)	23.5*	EDB CSA: 1.16 ± 0.65; EDB Th: 0.64 ± 0.21 MIL Th: 2.96 ± 0.83
		Control (n = 26)	16/10		25.2*	
				49 (25–67)		EDB CSA: 1.16 ± 0.65; EDB Th: 0.9 ± 0.10 MIL Th: 4.02 ± 0.36

(*continued on next page*)

Table 2 (*continued*)

Study with Downs & Black score		Participants				
		Characteristics	Sex (M/F)	Age (yrs)	BMI (*) (kg/m^2)	Significant differences ($p < 0.05$) Mean (±SD)
Wang et al., 2014 [67]	56%	T2DM + PN (n = 56) T2DM without PN (n = 50) Control (n = 50)	30/26 26/24 25/25	63 (7) 59 (10) 59 (7)	UTD	EDB CSA - Th ↓ FIS Th ↓ in both groups compared to control
Calvo Lobo et al., 2018 (a) [68]	89%	Hemiparesis foot Contralateral foot (n = 11)	4/7	62 (5)	19.5 (7.9)	(−)
Calvo Lobo et al., 2018 (b) [69]	89%	Hemiparesis feet (n = 20) Contralateral feet (n = 20) Control feet (n = 20)	10/10 10/10 8/12	61.5 (11.5) 61.5 (11.5) 50.1 (18.1)	21.6 (4.1) 21.6 (4.1) 22.6 (3.3)	FHB Th ↑ in hemiparesis and contralateral feet compared to control feet
Fraser et al., 2021 [70]	57%	CAI (n = 20) LAS (n = 17) Copers (n = 21) Control (n = 22)	5/15 8/9 8/13 9/13	20.9 (4.7) 21.8 (4.1) 20.8 (2.9) 19.6 (0.9)	25.1 (4.5) 24.1 (3.7) 23.7 (2.9) 22.5 (3.2)	No between-group differences in resting CSA
Hogan et al., 2020 [71]	78%	Plantar heel pain (n = 16) Matched controls (n = 16)	3/13 3/13	25.0 (2.2) 26.06 (1.7)	24.5* 24.1*	(−)
Jaffri et al., 2019 [72]	76%	MTP I arthrodesis Contralateral feet (n = 9)	3/6	57.56 (9.0)	30.6*	ABH CSA - Th ↓ FHB CSA - Th↓ FDB - Th ↓
Pompeo et al., 2021 [73]	72%	Patellofemoral pain (n = 20) Control (n = 20)	0/20 0/20	30.0 (5.6) 28.5 (5.1)	21.8 (2.4) 21.8 (1.3)	FDB Th ↓
Romero-Morales et al., 2019 [74]	72%	Achilles tendinopathy (n = 71) Control (n = 70)	(−)	45 (13) 35 (18.7)	24.8 (2.1) 23.88 (3.6)	ABH Th↑ FDB CSA - Th↑ FHB CSA ↑ FHB Th ↓

Abbreviations: M = male, F = female, yrs = years, kg = kilograms, m = meters, CSA = cross-sectional area, Th. = thickness, IFM = intrinsic foot muscles, ABH = abductor hallucis, FDB = flexor digitorum brevis, FHB = flexor hallucis brevis, QP = quadratus plantae, EDB = extensor digitorum brevis, FIS = first interstitial space, LUM1 = lumbrical 1, INT1 = interosseus 1, FDI = first dorsal interosseus, ADHO = oblique head of adductor hallucis, SMA = spinal muscular atrophy, ALS = amyotrophic lateral sclerosis, DM = diabetic mellitus, T2DM = type 2 diabetic mellitus, PN = polyneuropathy, CAI = chronic ankle instability, LAS = lateral ankle sprain * = author-based calculation of BMI.

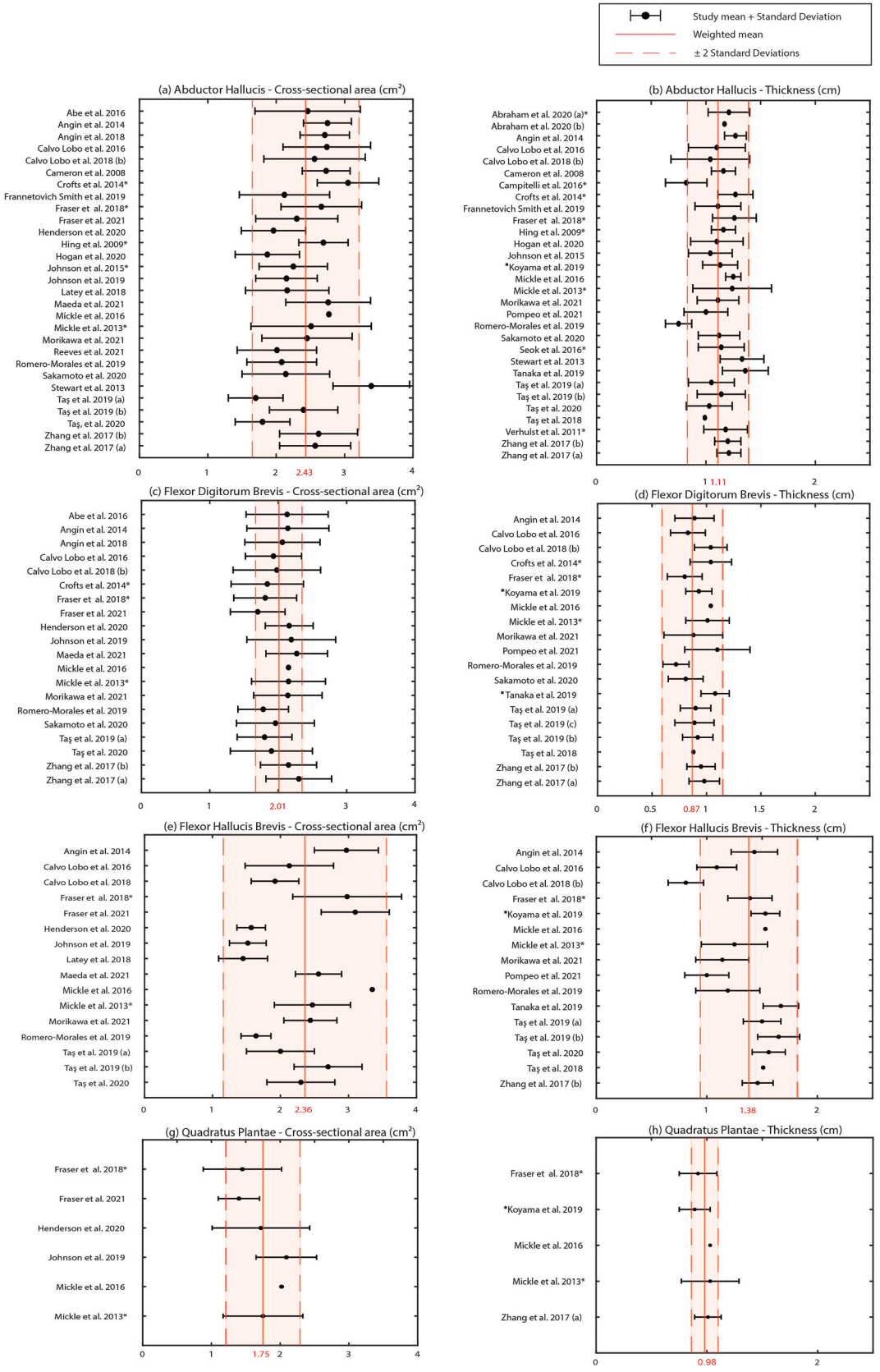
3. Results

3.1. Study selection

The initial search yielded 2075 records. After removing duplicates, this was reduced to 968 records. Articles were then screened by title, leaving 124 records eligible for full-text analysis. After applying the selection criteria, 53 papers were included for qualitative synthesis. No additional authors were contacted. A flow diagram is summarised in Fig. 1.

3.2. Characteristics of included studies

Descriptive data of asymptomatic participants are presented in Table 1, whilst descriptive data of symptomatic participants are included in Table 2. This also includes participants with a different foot posture, not necessarily with symptoms. A total of 21 studies involving asymptomatic participants have been retrieved, with a sample size ranging from 10 [23] to 80 participants [33]. Age of the asymptomatic participants ranges between 20 and 82 years. Abraham et al. did not include an average age but an age range, from 21 to 82 years [34], with six subjects older than 70 years. We included this study as the authors themselves state that only 6 out of 65 participants had an age above 70. BMI of all participants was normal [35], with the lowest BMI being 20.7 kg/m^2 [36] and highest BMI 28 kg/m^2 [37]. One study exceeded this significantly, with an average BMI of 29.6 kg/m^2 [38]. Nevertheless, it was taken for synthesis. Two studies assessed the IFM in elite sport athletes. Koyama et al. [39] assessed muscle thickness of ABH, FDB, FHB and QP in elite judo athletes and found no significant difference with matched physically active subjects. Tanaka et al. [40] found larger foot muscle thicknesses in well-trained male sprinters compared to non-sprinters. However, despite greater foot muscularity, muscle thickness was



(caption on next page)

Fig. 2. Reference values for cross-sectional area of the (a) abductor hallucis (c) flexor digitorum brevis (e) flexor hallucis brevis (g) quadratus plantae and dorsoplantar thickness of the (b) abductor hallucis (d) flexor digitorum brevis (f) flexor hallucis brevis and (h) quadratus plantae. Athletic populations are indicated with a square in front of the author's name.

not positively related to sprint performance. As an athletic population is characterized by muscle properties that may deviate from the general population, we have indicated this population with a square in Fig. 2.

Studies involving symptomatic participants exhibited a variety of foot pathologies and lower limb overuse injuries including neuromuscular diseases [53], hallux valgus [54,56,57,75], pes planus [58,60–62], diabetic neuropathy [38,65–67], hemiparesis [69, 68], ankle sprain/instability [70], plantar heel pain [71], first MTP joint arthrodesis [72], patellofemoral pain [73] and Achilles tendinopathy [74].

3.3. Methodological quality assessment

A total of 53 studies were assessed against the Downs's and Black checklist and attained a score of either moderate or high quality. Of the 53 articles, a total of 17 were of high quality (score >75%), the other 36 articles were of moderate quality (score: 50–74%). The average score was 71% and highest score 89% [69]. The majority of studies clearly reported inclusion/exclusion criteria and procedures for measuring the IFM. External validity was poor, with only a few studies stating the proportion of participating subjects compared to the total invited population [33,56,76,50]. Internal bias was low, with a total of 29 studies where the assessor was blinded to the majority of measures and procedures. Full quality assessment can be retrieved in **Appendix 3**.

3.4. Summary of results

3.4.1. 2D-MOUSE protocols

A plethora of 2D-MOUSE protocols have been used so far and an overview of the reference papers is presented in Table 3 whereas Table 4 provides an overview of their reported reliability measurements. Table 5 represents the intervention studies. We presented the reliability measures as described in the respective study. We were able to identify six studies that have developed and used reliable 2D-MOUSE protocols for measuring the IFM. Other studies were primarily based on these six protocols. The first study reporting reliability outcome measures was by Cameron et al., in 2008 [42]. They evaluated within and between-session reliability of ABH dorso-plantar thickness and CSA. Within-session reliability demonstrated subsequently excellent ICC's of 0.97 (95% CI: 0.99–0.99) for thickness and 0.98 (95% CI: 0.98–0.99) for CSA. Between-session reliability demonstrated excellent ICC's of 0.97 (95% CI: 0.95 to 0.98) for thickness and a good ICC of 0.79 (95% CI 0.65 to 0.88) for CSA.

In 2013, Mickle et al. proposed a protocol to identify thickness and CSA of ABH, FDB, FHB, ABDM and QP. This protocol was found to have good to excellent intra-tester reliability (ICC = 0.89–0.99), with limits of agreement between 8 and 30% of the relative muscle size [24]. However, aforementioned protocols only report intra-operator reliability. Therefore, Crofts et al. proposed a novel protocol and reported inter-rater reliability, with excellent ICC's for muscle thickness (ICC range 0.90–0.97) and CSA (ICC range 0.91–0.98) [23]. They report limits of agreement of 13–17% of relative muscle size. This protocol however only encompasses CSA and thickness measurements of the ABH, FDB and FHB. In 2018, Fraser et al. established test-retest reliability at rest and during active, resisted contraction and during IFM exercises. Reliability of ABH, FDB, QP, and FHB CSA and thickness resting measures were good to excellent

Table 3
Overview of current relaxed, non-weight bearing ultrasound protocols.

Author	Examiner	Device & Probe	Frequency	Number of images	Days between measures
Cameron et al., 2008	Novice researcher with training in US imaging over 3 months	Philips HD11 Ultrasound machine; Linear, 50 mm	5–12 MHz	3	3–7
Mickle et al., 2013	Chief investigator, with 8 years of experience in musculoskeletal ultrasound	Venue 40 portable musculoskeletal ultrasound system (GE Healthcare, United Kingdom); Linear	6–10.7 MHz	3	1–6
Crofts et al., 2014	One experienced (8 years) and one inexperienced (4 weeks) operator	Venue 40 portable musculoskeletal ultrasound system (GE Healthcare, UK); Linear, 12.7 mm × 47.1 mm	5–13 MHz	3	n.a.
Battaglia et al., 2016	2 years and 4 years of experience	GE Logiq E9 (GE Healthcare, Wauwatosa, WI; Linear (ML6-15)	9–12 MHz	/	/
Fraser et al., 2018	Physical therapist with 14 years of practice experience and 2 months of USI experience	Siemens acuson freestyle US system (Siemens, Mountain View, CA); Linear 3.8 cm	8 MHz	A previously measured US image was used for reference in identification of fascial borders and spatial orientation of each muscle	/
Franettovich Smith et al., 2019	1 year and 8 years of experience	LOGIQ S7 Expert (GE Healthcare); Linear	4.2–12 MHZ	/	6.8

Abbreviations: MHz = Megahertz, LoA = limits of agreement.

Table 4
Overview of reliability measures of current relaxed, non-weight bearing 2D ultrasound protocols for the intrinsic foot muscles.

Author	Population	Outcome parameter		Reliability measures						
				Intraclass Correlation Coefficients (ICC's)				Limits of agreement (LoA)	Standard error of the mean (SEM)	Minimal detectable change (MDC)
				Intrarater			Interrater			
				Within-session	Between session	Test-retest				
Cameron et al., 2008 [42]	Asymptomatic	ABH	CSA	0.97 (0.99–0.99)	0.79 (0.65–0.88)	n/a	n/a	n/a		
			Thickness	0.98 (0.98–0.99)	0.97 (0.95–0.98)					
Mickle et al., 2013 [24]	Asymptomatic	ABH	CSA	n/a	n/a	0.95	n/a	30%		
		FDB	Thickness			0.95		18%		
		FHB	CSA			0.99		8%		
		ABDM	Thickness			0.95		16%		
		QP	CSA			0.89		28%		
			Thickness			0.97		17%		
			CSA			0.98		16%		
			Thickness			0.97		18%		
			CSA			0.99		9%		
			Thickness			0.97		18%		
Croft et al., 2014 [23]	Asymptomatic	ABH	CSA	n/a	n/a	n/a	0.91	16%		
		FDB	Thickness				0.92	13%		
		FHB	CSA				0.98	17%		
			Thickness				0.96	13.5%		
			CSA				0.95	17%		
			Thickness				0.97	13.5%		
Battaglia et al., 2016 [37]	Asymptomatic	ABH	CSA	0.97 (0.94–0.99)	n/a	n/a	0.95 (0.88–0.98)	n/a		
		FDB	Thickness	0.95 (0.88–0.96)			0.72 (0.12–0.89)			
		QP	CSA	0.97 (0.93–0.99)			0.92 (0.78–0.96)			
			Thickness	0.85 (0.70–0.93)			0.74 (0.29–0.89)			
			CSA	0.92 (0.83–0.96)			0.77 (0.49–0.90)			
			Thickness	0.35 (−0.03–0.65)			0.57 (−0.19–0.84)			
Fraser et al., 2018 [44]	Asymptomatic	ABH	CSA	n/a	n/a	0.97–0.98	n/a	n/a	0.09 cm^2	0.26 cm^2
		FDB	Thickness			0.88–0.91			0.07 cm	0.18 cm
		FHB	CSA			0.91–0.93			0.13 cm^2	0.36 cm^2
		QP	Thickness			0.87–0.89			0.06 cm	0.15 cm
			CSA			0.95–0.98			0.14 cm^2	0.40 cm^2
			Thickness			0.76–0.83			0.09 cm	0.24 cm
			CSA			0.97–0.98			0.09 cm^2	0.25 cm^2
			Thickness			0.90–0.92			0.05 cm	0.14 cm
Franettovich Smith et al., 2019 [43]	Asymptomatic	ABH	CSA	0.99	0.97	n/a	0.98	n/a	0.06–0.13 cm^2	0.10–0.29 cm^2
		FIS	Thickness	0.97	0.92		0.85		0.03–0.08 cm	0.10–0.23 cm
			Thickness	0.98	0.81		0.86		0.05–0.17 cm	0.14–0.48 cm

Abbreviations: SEM = standard error of the mean; MDC = minimal detectable change, CSA = cross-sectional area, Th. = thickness, ABH = abductor hallucis, FDB = flexor digitorum brevis, FHB = flexor hallucis brevis, QP = quadratus plantae, n/a = not applicable.

Table 5
Summary of intervention studies using 2D-MOUSE outcome measures.

Study	Participants	Intervention group	Control group	2D-MOUSE outcome measures
Campitelli et al., 2016 [77]	Healthy individuals (n = 41)	Minimalist shoes: Restricted walking (n = 11); Unlimited walking (n = 11); Running (n = 10); 24 weeks	Traditional shod (n = 9)	ABH Thickness
Johnson et al., 2015 [78]	Recreational runners (n = 37)	Transitioning to minimalist shoes during 10 weeks (n = 18)	Traditional running shoes (n = 19)	CSA of ABH and FDB Thickness of FHB and EDB
Ridge et al., 2018 [79]	Recreational runners (n = 57)	Minimalist shoe walking (n = 19) Foot strengthening 8 weeks (n = 19)	No intervention (n = 19)	CSA of ABH, FDB and QP Thickness of FHB
Reeves et al., 2021 [80]	Healthy participants (n = 41)	Prefabricated orthoses, 3 months (n = 23)	No intervention (n = 18)	CSA of ABH and FDB Thickness of ABH, FDB and FHB
Protopapas et al., 2020 [81]	Pes planus (n = 18)	Custom-made foot orthotics for 12 weeks (n = 9)	No intervention (n = 9)	CSA of ABH, FDB and AbDM at baseline, 6 weeks and 12 weeks
Kim et al., 2015 [82]	Hallux valgus (n = 24)	Orthosis + toe-spread-out exercise, 8 weeks, 20min/day, 4 day/week (n = 12)	Orthosis only (n = 12)	CSA of ABH
Jung et al., 2011 [83]	Pes planus (n = 28)	Orthosis + short foot exercise, 8 weeks, 3 × 5 reps, 2x/day, everyday (n = 14)	Orthosis only (n = 14)	CSA of ABH
Namsawang et al., 2019 [84]	Flexible flatfoot (n = 36)	Short foot exercise + NMES, 4 weeks	Short foot exercise + placebo NMES	CSA of ABH
Okamura et al., 2020 [85]	Pes planus (n = 20)	Short foot exercise, 8 weeks, 3 day/week	Control group	Thickness of FDB and FHB

Abbreviations: ABH = abductor hallucis, FDB = flexor digitorum brevis, FHB = flexor hallucis brevis, EDB = extensor digitorum brevis, AbDM = abductor digiti minimi, CSA = cross-sectional area.

(0.76–0.98). Active and resisted measures and IFM exercises had moderate to excellent reliability (0.66–0.99). Standard error of measurement (SEM) of resting CSA thickness measures ranged from 0.09 to 0.14 cm^2 and 0.05–0.09 cm. Minimal detectable change (MDC) for CSA resting measures ranged from 0.25 to 0.40 cm^2 and 0.14–0.24 cm for thickness measures.

As the IFM function primarily during weight-bearing [1], Battaglia et al. proposed both a weight-bearing and non-weight-bearing protocol to measure CSA and thickness of the ABH, FDB and QP muscles [37]. Inter-rater reliability was moderate to good for all CSA measurements (ICC 0.57–0.95) and poor to moderate in thickness measurements (ICC range 0.49–0.74). However, a custom-built platform is required so the participant can support his/her weight while permitting the researcher access to image the medial and plantar foot muscles with an US probe. In response, Franettovich Smith et al. developed a more clinically feasible protocol in weight bearing while the foot is in contact with the ground. They demonstrated excellent within-session reliability (ICC > 0.94) and good between-session reliability (ICC > 0.81), as well as interrater reliability (ICC > 0.82) [43]. It is suggested that changes of 10–18% should be considered to exceed measurement error.

At the time of searching, no study was found reporting the validity of 2D-MOUSE measurements involving the IFM.

3.4.2. Reference values

2D-MOUSE measurements from ABH, FDB, FHB and QP are expressed as the pooled mean ± 2 standard deviations (SD) and is presented in Fig. 2. Total participants considered for pooled ABH CSA measurement were 781, for pooled FDB CSA measurement 595, for pooled FHB CSA measurement 465 and for pooled QP CSA measurement 124. Pooled samples included 1033 individuals for ABH thickness, for pooled FDB thickness measurement 647, for pooled FHB thickness measurement 495 and for pooled QP thickness measurement 127.

Based on the number of participants and each study mean, pooled means ± 2 SD for CSA measurements of the IFM were: ABH: 2.43 cm^2 ± 0.78, FDB: 2.01 cm^2 ± 0.34, FHB: 2.36 cm^2 ± 1.2 and QP: 1.75 cm^2 ± 0.54. When measuring muscle thickness, reference values of the IFM were: ABH: 1.11 cm ± 0.28, FDB: 0.87 cm ± 0.28, FHB: 1.38 cm ± 0.44 and QP: 0.98 cm ± 0.12.

3.4.3. Clinical outline in symptomatic populations

Table 2 provides an overview of studies where the morphology of the IFM was investigated in symptomatic individuals as providing reference values was not possible in the symptomatic population due to the limited number of studies. Significant differences are presented in relaxed, unloaded position.

Abraham et al. investigated relaxed and contracted muscle thickness in patients with amyotrophic lateral sclerosis and spinal muscular atrophy and found a smaller thickness in ADM ($p < 0.001$) and first dorsal interosseus space ($p < 0.001$) [53].

Four studies could be retrieved in subjects with hallux valgus [54,56,57,55]. Taş et al. investigated morphological features of ABH, FDB, FHB and found significantly smaller thickness and CSA of ABH ($p = 0.002$, $p = 0.003$) and FHB ($p < 0.001$, $p = 0.001$) in the hallux valgus population [57]. On the contrary, FDB thickness and CSA were larger (respectively, $p = 0.027$ and $p = 0.006$) [57]. Similar results were found by Calvo Lobo et al. where smaller thickness and CSA of ABH ($p = 0.02$, $p < 0.01$) and FHB ($p < 0.01$, $p < 0.01$) are reported. However, no significant difference in FDB thickness and CSA ($p = 0.19$, $p = 0.14$) was reported [55]. Aiyer et al. compared morphology of the ABH in hallux valgus between a 20–44 years old age group, a 45–64 years old age group and a 65+ age group. Increasing age was significantly associated with a reduction in thickness ($r = -0.27$, $p = 0.008$) and CSA ($r = -0.24$, $p = 0.019$) [54]. Stewart et al. imaged the ABH muscle in relationship to hallux valgus severity. Significant differences in thickness ($p = 0.001$)

and CSA ($p < 0.001$) between grade 0 and grade 2 and in thickness ($p < 0.001$) and CSA ($p < 0.001$) between grade 0 and 3 were noticed [56].

A total of seven studies could be retrieved where morphology of the IFM was assessed in participants with a different foot posture: pes planus, flat foot or pronation [58,60–62,59,63,64]. Angin et al. [58] reported significantly lower values in the pes planus group, ranging from −12.8% for CSA of the ABH muscle and −8.9% for CSA of the FHB. For thickness, percentual difference for ABH was −6.8% and −7.6% for FHB. No difference in CSA or thickness measurements of the FDB muscle could be observed. Sakamoto et al. [61] found significantly larger thickness of the ABH muscle in the flat foot group ($p < 0.01$). Thickness and CSA of AbDM ($p < 0.01$, $p < 0.01$) and thickness of the oblique head of adductor hallucis were significantly smaller ($p < 0.01$) [61]. Taş et al. found larger ABH thickness ($p < 0.001$) in the flat foot group, whereas both groups were similar in terms of FHB ($p = 0.627$) and FDB thickness ($p = 0.212$) [62]. Zhang and colleagues compared recreational runners who over-pronated with runners without over-pronation and showed that runners with over-pronated feet have 7.5% larger ABH thickness and 18.7% FDB CSA, whilst also having a −10.3% smaller CSA and a −12.3% thickness of the ABDM [63]. Two years later, they compared IFM morphology between recreational runners with a pronated foot posture and overuse injuries (symptomatic) and those without overuse injuries (asymptomatic). Symptomatic pronators demonstrated 19% smaller CSA and 14% smaller thickness of the ABH than their asymptomatic counterparts ($p < 0.05$) [64]. Okamura et al. compared muscle thicknesses of FDB and FHB and found no between-group differences between a pronated group and an overpronated group [60].

Four studies could be retrieved in diabetic (poly)neuropathy [38,65–67]. Dimensions of the EDB muscle were consistently significantly smaller in all studies compared to healthy controls except for the study of Kumar et al. [65], who reported no significant differences in EDB thickness. Wang et al. [67] and Kumar et al. [65] reported a combined measurement of the first metatarsal interspace while Severinsen et al. [66] reported discrete measurements of the first interspace (first lumbrical, first dorsal interosseus and the adductor hallucis). Combined thickness of the first metatarsal space was significantly smaller in diabetic patients compared to healthy controls, and even more small in diabetic patients with neuropathy [65–67]. Recently, Henderson et al. [38] also included evaluation of the thickness of the FDB and CSA of the ABH, FDB and QP muscle and found smaller IFM in early stage diabetic neuropathy.

Two studies compared CSA and thickness in poststroke patients [69,68]. Calvo Lobo et al. (a) [68] compared CSA of ABH, FDB and FHB of the hemiparesis foot to the contralateral foot. No between-group differences in CSA were found ($p > 0.167$). Later, they compared hemiparesis and contralateral feet to control feet, and found larger FHB thickness in the hemiparesis and contralateral feet ($p < 0.01$) [69].

Fraser et al. [70] assessed IFM dimensions in ankle injuries. No difference was found in CSA of the ABH, FDB, FHB and QP between a chronic ankle instability group, a lateral ankle sprain group, copers and a control group using ultrasound measurements in a relaxed, unloaded position.

Hogan et al. [71] compared ABH morphology in individuals with and without plantar heel pain. No significant group differences were found in CSA and thickness.

Jaffri et al. [72] determined differences in the size of the ABH, FDB and FHB after arthrodesis of the 1st metatarsophalangeal joint by comparing the surgical with the contralateral asymptomatic foot during sitting and standing positions. The CSA and thickness of the ABH and FHB of the surgical foot were significantly smaller than that of the contralateral foot, and this in both positions ($p < 0.05$). For the FDB, only a significant difference was found during standing, with the surgical foot having a smaller thickness compared to the contralateral foot ($p < 0.05$).

Pompeo et al. [73] compared morphology of the ABH, FDB and FHB muscles in women with and without patellofemoral pain. Women with patellofemoral pain had smaller FDB thickness ($p < 0.01$).

Romero-Morales et al. [74] compared thickness and CSA of the ABH, FDB and FHB in persons with and without chronic midportion Achilles tendinopathy. ABH ($p < 0.001$) and FDB ($p < 0.001$) thickness, as well as FDB ($p = 0.005$) and FHB CSA ($p = 0.048$), were larger in the tendinopathy group. On the contrary, FHB muscle thickness ($p < 0.001$) was larger in the control group.

4. Discussion

We identified 53 studies that used 2D-MOUSE to assess the IFM and pooled these results to obtain reference values in asymptomatic adults. We provide a visualization of the CSA and thickness of the IFM reported in current literature. For each muscle, means and SD of each study are visualised, along with indication of the weighted mean. This provides a precise illustration of the variation in IFM dimensions across the population and a valuable resource for future research and more clinically oriented studies. Pooled sample sizes were quite variable, ranging from 127 participants for QP thickness to 1033 for ABH thickness. It should be noted that there is a high variability in dimensions of the IFM, which can mainly be explained by the heterogeneity of the different populations and the lack of normalisation for other variables: sex, height, body size, foot posture and physical activity. Another factor could be anatomical variability. This is especially true when evaluating the flexor hallucis brevis muscle, which delineation is more difficult to identify on US due to its obliquely oriented muscle fascicles.

Various measuring protocols have been put forward, with good to excellent established reliability in both an unloaded [23,24,37,42] and a loaded position [37,86]. We reported good reliability between and within operators for several US protocols. Cameron et al. [42], Mickle et al. [24], Crofts et al. [23] and Battaglia et al. [37] assess the ABH muscle in a supine position and other plantar muscles in a prone position. Frannetovich Smith et al. [43] position the participant in a sitting rather than lying position, with both feet placed on the floor, which may be more comfortable for those suffering from e.g. back problems. Weightbearing did not reduce intra- or interexaminer reliability and all IFM exhibited a significant increase in CSA [37]. In summary, we notice a general trend of good to

excellent reliability in every protocol. This despite the many variables which can influence the protocol as summarised in Table 3: the difference in education and experience of the sonographer and the particular details of the protocol itself; device and type of probe, frequency, number of images taken and days between measurements. However, we would still advocate structured training and education in operator skills.

At the time of searching, we could not retrieve a study determining the validity of US measurements for the IFM. However, recently, a study was published by Swanson et al. [87], demonstrating strong agreement between US imaging and MRI for the ABH, FDB, QP and ADM muscles, though MRI retained higher precision and reliability. This underlines that dedicated training in US imaging remains important as this will undoubtedly lead to better image capturing and more reliable measurements of the IFM.

Differences in IFM morphology have not been studied extensively in symptomatic populations. Only single studies exist investigating the morphology in ankle instability, plantar heel pain, MTP I arthrodesis, patellofemoral pain, and Achilles tendinopathy. Therefore it's yet impossible to detect a clear trend and further research in these populations is warranted. In populations with hallux valgus, pes planus, diabetic neuropathy and stroke patients more studies could be retrieved. Thickness and CSA of the ABH and FHB muscle are significantly smaller in every retrieved hallux valgus study. Calvo Lobo et al. [75] stated no significant differences in FDB muscle size, while Taş et al. [57] showed greater CSA and thickness of the FDB in individuals with hallux valgus. A higher CSA of the FDB muscle may suggest a compensation against mechanical changes in the foot, thus increasing the loading on the FDB muscle, causing hypertrophy.

4.1. Limitations

This study has several limitations. First, the last item of the Downs and Black checklist examining the power of results was simplified to a score of 0 (no sample size calculation) or 1 (sample size calculation reported). This dichotomous approach is an oversimplification of study power and is a clear limitation in the quality assessment process.

Second, a single reference value as presented here, only paints a limited picture of reality as several factors such as age, sex, BMI, athletic status and foot phenotype affect intrinsic foot muscle size [70,88]. More studies including a larger population are needed to further investigate the relation between these factors and IFM dimensions and would also allow us to determine reference values for each subpopulation. However, the number of studies investigating IFM morphology is too limited to investigate the impact of these different variables via normalisation. This would be an excellent goal for future studies, but the current manuscript aims to provide reference values for the dimensions of the intrinsic foot muscles in the populations studied up to now. Nevertheless, we are the first to provide an example of reference values for the intrinsic foot muscles and highly recommend to take these variables into close consideration when comparing to our reference values.

Thirdly, values reported here are for an asymptomatic population of recreationally active adults with cut off age at 65 and cannot be used as reference values for an elderly population. Several studies have underlined the importance of intrinsic foot muscle strength in balance and falls in older adults [89]. For this reason we placed an upper limit of 65 years and restricted our target population as we believe this might be an interesting venue for future research.

Finally, we summarised the clinical applicability of 2D ultrasound for the IFM by comparing it to a symptomatic population. These comparative studies however are cross-sectional in nature and therefore causality cannot be determined. Ultimately, evaluating the intervention studies could be a topic for another review to work out in depth. Therefore, we recommend to be careful when interpreting these data. We should also note that there are more studies using 2D ultrasound to evaluate intrinsic foot muscles than the 9 studies we have presented here. However, the outcome measures of these studies are different from what we have examined. For example, Fraser 2019 and Lee 2019 use 2D ultrasound to evaluate intrinsic foot muscles but their outcome measures are ultrasound activation ratios (contracted/relaxed) [13,14].

4.2. Clinical implications

Scientific interest into IFM function has increased significantly in the last decade since there is growing evidence that adequate IFM strength is a cornerstone of efficient sport and daily life performance. Therefore there is great merit in investigating the value of 2D-MOUSE in assessing the IFM as its low cost, non-invasiveness, accessibility and reliability are perfectly suitable in clinical practice.

5. Conclusion

Current protocols show an overall good to great reliability. We have formulated reference values for musculoskeletal ultrasonography of the ABH, FDB, FHB and QP muscles in an asymptomatic adult population. We encourage these data to be used by medical and paramedical practitioners to guide detailed assessment of the intrinsic foot musculature. In addition, we characterised clinical differences in IFM morphology in symptomatic populations. Based on current literature there is evidence of different IFM size in several foot pathologies however, limited evidence still exists in common overuse injuries such as plantar heel pain, patellofemoral pain, and Achilles tendinopathy.

Author contributions

Nicolas Haelewijn: Conceptualization, Database search, Quality evaluation, Data extraction Writing – original draft, Jean-Louis Peters Dickie: Quality evaluation, Data extraction, Filip Staes: Conceptualization, Writing – review & editing, Evie Vereecke:

Writing – reviewing & editing, Visualization Kevin Deschamps: Conceptualization, Writing – review & editing Supervision, Project Administration. All authors have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted.

Data availability statement

Data included in article/supp. material/referenced in article.

Additional information

Supplementary content related to this article has been published online at [URL].

Funding

This research did not receive any specific grant from any funding agencies in the public, commercial, or not-for-profit sectors.

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.

Acknowledgements

The authors would like to thank the librarian Krizia Tuand for assisting in the design and implementation of the electronic literature search.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e18252.

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