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Original Article

Surface electromyography of the foot: A protocol for sensor placement

Helen Branthwaite[a,*], Christopher Aitkins[a], Steven Lindley[b], Nachiappan Chockalingam[a]

[a] Centre for Biomechanics and Rehabilitation Technologies, Staffordshire University, Stoke on Trent, UK
[b] Delsys Europe Ltd., Manchester, UK

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ABSTRACT

Background: The use of surface EMG (sEMG) to record muscle activity is common place yet due to restrictions in technology studies on the intrinsic foot muscles have been limited or only fine wire instruments have been used.
Aim: This paper looks at the potential reliability of a sEMG protocol for assessing the intrinsic foot muscles.
Methods: Six intrinsic muscles were defined using ultrasound and muscle function testing. A protocol for sensor placement was created with repeatability and reliability testing of the protocol conducted by three separate testers on three subjects over two different time frames. Inter tester and Inter session repeatability and reliability was measured with ICC and percentage standard error of measurement.
Results: Although there was good correlation between Extensor Digitorum Brevis, Dorsal Interossei, Abductor Digiti Minimi and Flexor Digitorum Brevis there was increased variability and poor correlation for Flexor hallucis Brevis and Abductor Hallucis. The percentage standard error of measurement did not support the high ICC values indicating a lower precision of measurement.
Significance: Variability between testers and sessions shows an inconsistent reliability of sEMG and further work is required with protocols focussing on grouping muscles to improve the understanding of the intrinsic foot muscles.

1. Introduction

Electromyography (EMG), the study of the muscle function through inquiry of the electrical signal the muscles emanate [1], has been explored since Luiggi Galvani in 1791, whereas the study through surface EMG (sEMG) was not introduced until Piper in 1912. Since these early works, the equipment available for detecting sEMG has evolved dramatically and allows researchers, practitioners and clinicians access to the rich neurophysiological data sEMG can offer. Studying muscle function through sEMG however requires adherence to strict guidelines to ensure the physiological data is truly represented and interpreted. Specific guidelines for sEMG sensor placement allow for standardised methodologies, thus to reduce variation in sEMG measures across laboratories or clinics and on different participants [2]. Such guidelines currently make sEMG sensor placement recommendations for a selection of commonly investigated muscles, but there lacks evidence-based protocol on sEMG sensor placement for many muscles, including the muscles of the feet.

Intrinsic foot muscles are small and thus pose difficulties in isolating anatomically and physiologically correct placement of sEMG sensors. The Abductor Hallucis is a superficial muscle located on the medial border of the foot and sEMG of this muscle has been examined during various movements, including standing from a seated position [3], performing Hallux exercises [4], performing arch exercises [5] and with the use of foot orthoses [6]. There is little explanation in these studies to define the location of the sEMG electrodes to gather data from abductor hallucis, making repeating these protocols difficult to reproduce.

Further work on other intrinsic foot muscles include using sEMG to study the activity of Extensor Digitorium Brevis and Flexor Digitorium Brevis during walking but again there is limited anatomical location and description of sensor location [7]. The lack of standardised sensor location for sEMG of the intrinsic foot muscles leads to large variability to exist between research groups and limits comparisons and collaboration.

There has been an attempt to develop standardised protocols for sEMG of the intrinsic foot muscles [8] which explains a more specific anatomical landmark description for sensor placement and utilises ultrasound to locate the muscle belly of Abductor Hallucis. The expansion of this work to consider further intrinsic foot muscles and provide clear protocols for clinicians and researchers to capture meaningful and repeatable sEMG data could lead to better quality research findings and clinical applications. Therefore, the initial aim of this report is to define a protocol for sEMG sensor placement of the foot with a secondary aim of testing the inter and intra reliability of the protocol with signal

* Corresponding author at: Staffordshire University, Brindley Building, Leek Road, Stoke on Trent, ST4 2DF, UK.
E-mail address: h.r.branthwaite@staffs.ac.uk (H. Branthwaite).

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quality objective measures for novice investigators.

2. Method

2.1. Establishing the sEMG protocol

The initial experimental testing was to identify a protocol to define which of the intrinsic muscles are recruited for the movements of the foot and digits, specifically flexion/extension and abduction/adduction of the digits as well as discrete rotation of the midfoot. One female participant (42 years 66 kg, 174 cm) was recruited and consented for exploratory investigations on muscle location and function of the right foot. An Ultrasound, probe MSK LA523E (Esaote, Mylab25, Italy), was used to define the intrinsic muscles of the foot accompanied with isolated muscle testing of movement in all 3 planes of the foot accompanied with flexion/extension and abduction adduction of the digits. This enabled assessment of how each muscle contributed to movement and gave an objective measure of these movements [9–11]. This combined assessment of ultrasound [8] and muscle function [10,11] resulted in the following 6 intrinsic muscles being identified, with specific functional tests, as key for motions of the foot and therefore were selected for the assessment of sEMG, (muscles overlying each other and in close proximity were amalgamated as one):

Extensor Digitorum Brevis (EDB)
Dorsal Interossei (DI)
Abductor Digiti Minimi (AbdDM)
Flexor Digitorum Brevis (FDB)/Quadratus Plantae (QP)
Flexor Hallucis Brevis (FHB)
Abductor Hallucis (AbH)

From the 6 identified muscles, the midpoint of the muscle was defined by ultrasound [9] and relevant marks were made on to the skin in removable pen. The sEMG sensors were then placed on the midportion of the muscle aligned with the orientation of the muscle fibre direction and affixed to the skin. Initial sensor placement was tested using the Delsys Trigno system (Delsys Inc., Natick, MA) and the associated Delsys EMGworks Acquisition (version 4.2, Delsys Inc., Natick, MA) software. The sensors utilised were 6 × Delsys Trigno Mini Sensors (Sampling rate 1926 Hz; 16-bit resolution; 20 ± 5 Hz–450 ± 50 Hz bandwidth filter; 909 V/V gain and 10 mm inter-electrode distance) for which the reference electrode component was placed on the distal third of the tibia (Fig. 1).

Extensive pilot sEMG signal testing were completed on each of the defined muscles. The participant was asked to complete muscle tests for each of the 6 muscles defined by Kendall et al. [11]. This included toe flexion/grip, toe extension, toe splay, hallux flexion and abduction against resistance. The sEMG sensor location was modified for each muscle based on the quality of the signal for each test. On satisfactory signal recording 3 × maximum voluntary contractions (MVC) Tasks, with 5 repetitions were recorded for repeatability. The final anatomical position of the sensor placement was then recorded to describe the final protocol (Table 1).

2.2. Reliability of sEMG protocol for intrinsic foot muscles

After approval from the University Research Ethics Committee, an experimental study was conducted to examine the validity and reliability of the determined sEMG protocol. Three volunteer novice sEMG testers consented to take part, all three testers had not used sEMG before the protocol was provided. Data was collected from 3 randomly recruited participants (1 = Female/32 years 2 = Male/48 years/68 kg/169 cm 3 = Female/41 years/63.5 kg/171 cm) who also consented to taking part in testing which was undertaken across two separate sessions 5 weeks apart.

The protocol (Table 1) was individually issued to the 3 testers (A,B & C) and included description of how to prepare the sensors and the skin for measurement. Participants, who had no prior training for the foot exercise tests, were asked to lie prone, roll up the trouser leg of their right foot and follow the instructions of the tester. All testers applied the sEMG on all six muscles of each participants' right foot. This was undertaken in a blinded scenario where no tester observed other testers whilst placing the electrodes on the participant. The participants were then asked to undertake three MVC tasks (held for 5 s), with five repetitions 30 s rest period between each contraction. The MVC tasks were chosen to give maximum contraction of all 6 muscles during gross movements of the forefoot digits to ensure that activity of the muscles was detected. These actions were performed with no resistance and participants were asked to:

1) Maximum flexion of digits
2) Maximum extension of digits
3) Maximum spread of all digits

Then the six individual muscle function tests that isolated that muscle (Table 1) were performed using the same regime, 5 s of contraction, 5 times with a 30 s rest period between each contraction, to isolate muscle activity from each of the defined muscles above. This methodology was then repeated 5 weeks later (Session 2) using the same testers, participants and protocol.

3. Data processing and analysis

The sensors themselves have an analog filter (20 ± 5 Hz–450 ± 50 Hz bandwidth filter). The raw sEMG collected through these sensors was used to gain a Root Mean Square (RMS) of

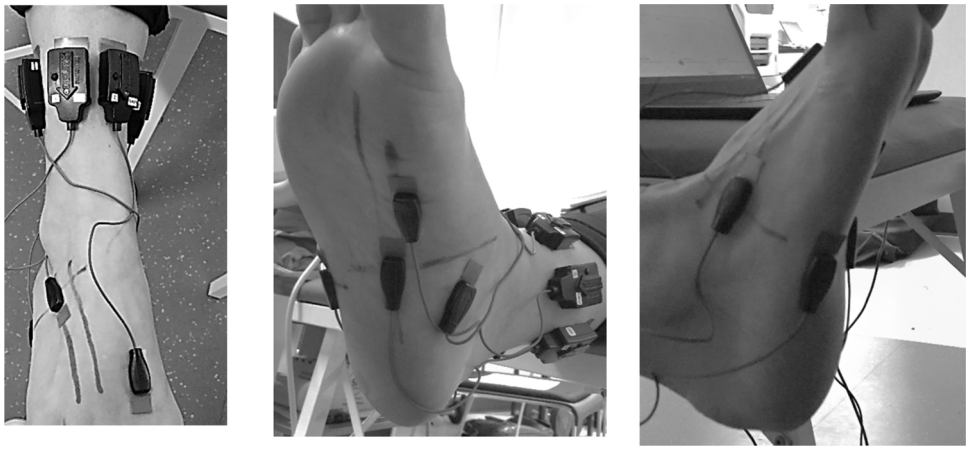
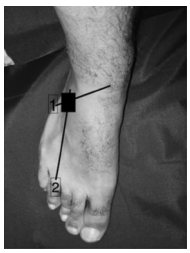
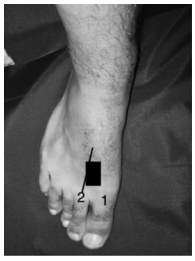
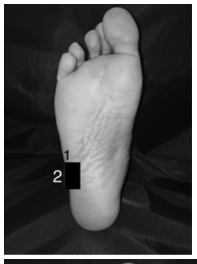
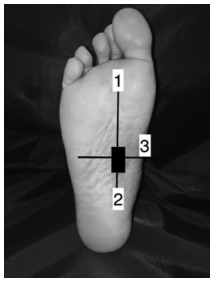
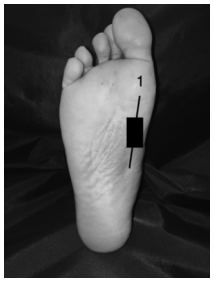
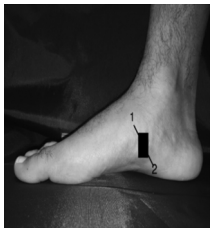


Fig. 1. Pilot sensor placement, sensors were moved along the line of the muscle defined from the ultrasound shown as marks on the skin.

Table 1
sEMG placement protocol describing anatomical position and muscle test with QR codes for video demonstration.

Muscle tested	Anatomical placement	Sensor placement	Muscle testing activity (Kendall et al. [11])	QR code link for video demonstration
Sensor 1 Extensor digitorum brevis	Styloid process (base the 5th metatarsal) trace a line vertically towards the dorsum (top) of the foot [1]. Trace a line along the dorsum (top) of the 4th Metatarsal from the metatarsal head [2]. Where the lines intersect place **sensor 1**.		Hold the foot and ankle in a plantarflexed position. The subject extends lesser toes against a flexion force placed on the proximal phalanx	
Sensor 2 Dorsal interossei	Palpate the space between the 1st metatarsal head [1] and the 2nd metatarsal head [2]. Place **sensor 2** in this space halfway along the length of 2nd metatarsal.		Hold the foot and ankle in a neutral position, allowing movement of the metatarsophalangeal joints. The subject flexes the lesser digits, while resistance is applied to the proximal phalanxes	
Sensor 3 Adductor digiti minimi	On the plantar surface of the foot locate the styloid process (base of the 5 metatarsal) [1]. Place **sensor 3** posterior to this at calcaneal cuboid joint [2].		Hold the foot and ankle in a neutral position. The subject moves the 5th digit laterally against a force applied in a medial and slightly plantar-ward direction	
Sensor 4 Flexor digitorum brevis Quadratus plantae	On the plantar aspect of the foot trace a line along the shaft of the 2nd metatarsal to the head to the medial calcaneal tuberosity [1,2]. Then from the navicular tuberosity trace a line to the plantar of the foot [3]. Where the lines intersect place **sensor 4**.		Hold the foot and ankle in a plantar flexed position with the metatarsophalangeal joints hold to prevent plantarflexion. The subject curls lesser digits while extension resistance is applied	
Sensor 5 Flexor hallucis brevis	Plantar surface of the foot from the 1st metatarsal head [1] place **sensor 5** half way along the metatarsal shaft.		Hold the foot and ankle in a neutral position. The subject flexes the hallux against an extension force applied to the proximal phalanx	
Sensor 6 Abductor hallucis	Trace a line from the navicular tuberosity to the medial calcaneal tuberosity [1,2]. Place **sensor 6** at the midpoint on this line.		Hold the foot and ankle in a neutral position. The subject resists a laterodorsal force applied to the hallux	

the background noise as well as the contraction signal. This was computed using Matlab (version R2015b) with an RMS moving average (1 – second) window filter.

These values were then processed to give a Signal to Noise Ratio (SNR), for each sensor location during each contraction. SNR is a dimensionless ratio of signal power to noise power within a recording [11]. The mean and standard deviation (SD) of SNR across the 5 repetitions for each task for each participant was computed for:

1) *Inter-tester*, reliability of data between testers,
2) *Inter-session*, reliability of data between time frames,

Additionally, an Interclass Correlation Coefficient test, which adopted a two way mixed absolute average measures model, was completed from the processed SNR [12]. A value of above 0.75 is considered as good reliability [13]. This was completed using Statistical Packages for the Social Sciences (SPSS) software produced by IBM. Additionally, to assess the reliability of the data, a Standard Error of Measurement (SEM) and %SEM test was performed [14], using the following calculations:

$$SEM = S_x\sqrt{1} - ICC$$

Where S_x is the pooled SD for either Day 1 and Day 2 or tester ABC. Depending on the outcome measure; inter-tester variation and inter-session variation [15]. With the SEM being expressed as a percentage of the grand mean, for example:

$$\%SEM = \frac{SEM}{x^1 + x^2} \times 100 \quad \%SEM = \frac{SEM}{y^1 + y^2 + y^3} \times 100$$

where x^1 is the means of trials on day 1 and x^2 is the means of trials on day 2 for each tester ABC and then, y^1 is the means of trials for tester A, y^2 is the means of trials for tester B and y^3 means of trials for tester C for each day 1 and 2.

4. Results

4.1. Inter-tester

Between the testers A, B & C there was a good repeatability for each muscle at either day one or two with participant 2 having more reliable outputs. Equally though, low repeatability was also observed for each participant for FHB and AbH. However, although the ICC scores appear to show good repeatability for some muscles, the %SEM for these muscles do not support this correlation measurement, with high %SEM observed indicating lower precision of measurement between testers.

Individually, the ICC for each muscle indicated that EMG measurement for EDB was the only muscle that showed good correlation between testers for each participant. Participant 1 shows the greatest variability for each muscle between testers and only had good repeatability for Extensor Digitorum Brevis, ADM and Abd Hal. Participant 2 appeared the most reliable participant for the protocol with all muscles having good reliability apart from ADM and Abd Hal (Table 2).

4.2. Inter-session

Similar results were observed over testing between days, showing less reliability for each tester with minimal correlation between data, particularly for Participant 1. There were again some strong ICC values from participant 2 and 3 for the DI and FDB muscles, but again the % SEM data did not support this (Table 2).

5. Discussion

Any research involving human participants, runs the risk of poor generalizability [16,17]. The lack of a consistent correlation between testers and time frames within this protocol, shows that sEMG of the intrinsic muscles of the foot is not yet reliable or repeatable and produces data with great variability. Fine wire protocols that have explored the same intrinsic muscles appear more reliable [18] but these methods are intrusive and can be restricted to the larger intrinsic foot muscles. Similarly, an array of sensors has been used to estimate muscle function of the intrinsic foot muscles [19] this method creates a generalised model of activity rather than identifying individual muscles.

The importance of quantifying the muscle activity of the intrinsic foot muscles is evident in key thematic areas of biomechanics research and clinical applications such as: the function of the Diabetic foot [20,21]; barefoot and minimalist footwear [22,23]; toe strength and falls risk [24–26]. The current report was aimed at developing a sEMG protocol to enable mores specific measurement of intrinsic foot muscles to enable a greater understanding of the significance in pathology.

The protocol that was developed underwent pilot testing prior to actual data collection to reduce the possibility of anatomical variation between subjects and poor sensor placement between testers. However, even though all ultrasound images taken were accurate and matched previous studies reporting on intrinsic muscle architecture [9,27] there were restrictions in knowing if the EMG data collected was purely from contraction of the individual muscle defined or a combination of signals. This is a main restriction with sEMG of the intrinsic foot muscles as the anatomy is complex with muscles influencing other muscle activity based on the origin and innervation [28]. Even though the exercises used for activation of the muscles are clinically current and have been used in previous studies [3–5,29] a grouping of actions rather than

Table 2
ICC (above 0.75 in bold for good reliability) and %SEM for each Participant 1,2 & 3 for each muscle (EDB extensor digitorum Brevis, DI dorsal interossi, ADM abductor digit minimi, FDB/QP flexor digitorum brevis quadratus plantae, FHB flexor hallucis brevis, AdH adductor hallucis) inter-tester AB&C on day 1 and day 2 and inter-session between day 1 and day 2 for each tester AB&C.

Muscle	Test	Participant 1		Participant 2		Participant 3	
		ICC	%SEM	ICC	%SEM	ICC	%SEM
EDB	ABC D1	0.44	62.41	***0.85***	29.43	***0.77***	32.06
	ABC D2	***0.94***	16.20	0.64	33.07	0.73	33.47
	D1 v D2 A	−0.04	51.05	0.29	48.69	0.73	33.33
	D1 v D2 B	0.65	43.49	***0.90***	20.12	0.72	34.77
	D1 v D2 C	0.72	44.45	***0.87***	26.13	***0.79***	30.83
DI	ABC D1	0.37	59.33	***0.92***	38.14	***0.82***	32.62
	ABC D2	0.42	36.89	***0.93***	32.51	0.63	47.38
	D1 v D2 A	−1.42	60.45	***0.98***	17.43	0.23	70.92
	D1 v D2 B	0.35	54.19	***0.86***	51.22	0.52	47.77
	D1 v D2 C	−0.11	70.09	***0.91***	37.39	***0.94***	20.09
ADM	ABC D1	0.46	54.65	0.67	26.45	0.71	23.56
	ABC D2	***0.81***	29.74	0.53	45.27	***0.76***	21.82
	D1 v D2 A	0.81	28.90	***0.81***	21.07	0.57	29.21
	D1 v D2 B	***0.77***	30.58	0.19	64.25	0.42	31.99
	D1 v D2 C	0.37	62.57	0.40	42.26	***0.80***	19.83
FDB/QP	ABC D1	***0.75***	22.14	***0.93***	20.14	***0.76***	27.59
	ABC D2	−1.30	52.95	***0.91***	19.73	***0.94***	17.55
	D1 v D2 A	−0.77	50.03	***0.85***	27.24	***0.82***	25.28
	D1 v D2 B	0.58	30.32	***0.84***	31.42	0.61	39.66
	D1 v D2 C	−2.00	55.33	***0.87***	23.22	***0.90***	21.06
FHB	ABC D1	−0.20	73.36	***0.86***	37.81	0.49	57.05
	ABC D2	0.40	50.87	***0.83***	32.91	0.26	46.89
	D1 v D2 A	−0.84	78.53	0.68	53.28	0.28	73.16
	D1 v D2 B	0.69	46.25	0.57	51.19	−0.88	80.74
	D1 v D2 C	−0.27	67.47	***0.84***	38.07	0.58	40.86
AbH	ABC D1	0.41	71.01	0.09	60.48	0.52	37.78
	ABC D2	***0.83***	28.97	−0.09	79.80	0.71	28.75
	D1 v D2 A	0.66	47.07	0.04	40.02	0.27	36.99
	D1 v D2 B	0.60	47.52	0.37	68.64	−0.43	90.56
	D1 v D2 C	0.66	47.07	−0.20	84.70	0.49	32.54

identifying specific muscles to test could give direction into extending future work. Alternative methods for sensor placement could have included identifying the MUAPP (Motor Unit Action Potential Point) as this has been highlighted as the point at where a muscles activation is strongest [30]. However, this would have been challenging to stimulate the smaller deeper muscles and ultrasound was deemed as most appropriate and has been identified as reliable for identifying intrinsic foot muscles [31].

Additional sources of data variability that provided lower precision of measurement came from the three subjects tested, whose intrinsic foot muscles provided an inconsistent wide range of data from the testing. The recruitment of the subjects tested were not assessed for strength and ability to recruit the individual muscles. Neither were the subject's experts in activating these muscles. Chapman et al. [32] found that muscle recruitment can be highly developed and easily defined in expert cyclists and poorly developed in novices. Exploration of ability to activate the intrinsic foot muscles may present different results. However, the intrinsic foot muscles are reported as being weak or dormant in older people [24,25] and it is unclear at what time over a life span this weakness occurs. An inability to contract the intrinsic muscles immediately could have occurred as testing commenced with a learnt response or conditioning of the muscles throughout the testing, increasing the activity within a trial leading to variability for each subject.

Research reporting sEMG of the foot should be interpreted with caution as the protocol for sensor placement and the challenges of the anatomy of the foot still need to be advanced. The use of small sensors is useful to use in delicate and specific areas however the noise from vibration and adjacent and deeper tissue made the variability of the data large and reduced the reliability of the data collected. Crosstalk is a phenomenon, which is a result of the electrical conductivity of the soft tissues of the body, for the intrinsic muscles there is a high risk of signal crosstalk as well as signal contamination as muscles work in unison to perform the movements requested [33,34]. As a muscle in one location contracts, due to the electrical stimulation, the electrical signal is detected by a sensor placed in a different location. Therefore, due to the anatomy and architecture of the small intrinsic foot muscles the cross talk of signals remains high.

Large number of data trials with selective data cropping to reduce the range of data could be a suitable way to manage data in future. However, the challenges of recording intrinsic foot muscle activity remain high for good reliable data to be produced.

6. Conclusion

Ultrasound was successfully used to identify the intrinsic muscles of the foot: EDB, DI, ADM, FDB, FHB and AbH to produce a protocol for sEMG application of sensors to assess the contraction of these muscles. The inter-tester and inter-session variation for the muscles tested showed some good repeatability and reliability but there was increased variability in the data collected. The protocol outlined in this paper gives an insight into the challenges of gaining valid information and understanding of the intrinsic foot muscles and the function with sEMG. Further work on data collection and trial variability is recommended to advance the recording of foot sEMG, with a particular focus on grouping the muscles for performing specific movements within the foot.

Conflict of interest

There was no conflict of interest in conducting this study. This study was completed as a University internally funded project and was part of Christopher Aitkins MSc Clinical Biomechanics. Steven Lindley as an employee of Delsys Europe had no conflict of interest in this work and supported the study with data collection and analysis.

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