



Reliability of a clinical 3D freehand ultrasound technique: Analyses on healthy and pathological muscles

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ABSTRACT

Background and objective: 3D freehand Ultrasonography is a medical imaging technique that can be used to measure muscle and tendon morphological and structural properties, including volume, lengths and echo-intensity. These properties are clinically relevant in neurological disorders such as spastic cerebral palsy to monitor disease progression and evaluate the effect of treatment. This study presents a methodology for extracting these parameters along with a clinical reliability analysis for the data acquisition and processing.

Methods: The medial gastrocnemius muscles and Achilles tendon of 10 typically developing children and 10 children with spastic cerebral palsy were assessed. An open-source in-house software library developed in Python (Py3DFreeHandUS) was used to reconstruct, into one 3D data set, the data simultaneously acquired from an US machine and a motion tracking system. US images were manually segmented and linearly interpolated by means of a new simplified approach which involved sequentially decreasing the total number of images used for muscle border segmentation from 100% to 5%. Acquisition and processing reliability was defined based on repeated measures from different data processors and from different data acquirers, respectively.

Results: When only 10% of the US images were outlined, there was an average underestimation of muscle volume of 1.1% and 1.6% with respect the computation of all the available images, for the typically developing and spastic cerebral palsy groups, respectively. For both groups, the reliability was higher for data processing than for data acquisition. High inter-class correlation coefficient values were found for processing and acquisition reliability, with worst case values of 0.89 and 0.61, respectively. The standard error of measurement, expressed as a percentage of the average volumes, was smaller than 2.6 ml (4.8%) in all cases. **Conclusions:** The present analysis demonstrates the effectiveness of applying 3D freehand ultrasonography in a clinical setting for analysing healthy and pathological paediatric muscle.

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1. Introduction

Among other contributing factors, muscle morphology is a crucial component influencing muscle function. Parameters such as muscle volume and length can provide insight into abnormal muscle behaviour that may be associated with decreased function [1]. These parameters can be altered in various musculoskeletal and neurological disorders, such as spastic cerebral palsy (SCP) [2,3]. Previous studies have reported a reduction of muscle volume and

length for the medial gastrocnemius (MG) in children with SCP [4,5]. Muscle composition can also be altered due to an increase in internal fat and fibrous content with a decrease in water particles [6,7]. All these alterations can be quantified using volumetric medical imaging.

2D ultrasonography (US) is a non-invasive medical imaging modality that can easily be applied to multiple sites of the body [8]. However, 2D US is confined by the width and tissue depth penetration of the US transducer [9], not allowing visualisation of the entire muscle and tendon [10]. 3D freehand US (3DfUS) is a technique capable of coping with this drawback by combining a conventional 2D US system with a pose (position and orientation) sensor attached to the US transducer [11,12]. This results in volumetric data sets. 3DfUS has recently been gaining popularity due to

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advancements in software and hardware performance, making it suitable for several clinical applications [13].

3DfUS validation analysis in-vitro and on animals showed promising results [14]. These were also satisfactory when analysed in-vivo for the MG muscle of healthy adults, by showing good agreement with respect the data extracted from magnetic resonance imaging [15,16]. Furthermore, satisfactory reliability results were found [16]. These parameters were obtained with the lower leg submerged in a water tank, which aids in limiting acquisition errors such as US transducer pressure over the skin. However, the use of a water tank is not convenient for routine use, hence the reported reliability values may not be entirely representative. Routine investigations on lower limb muscles are instead carried out using copious amounts of acoustic streaming gel in between the US transducer and the skin [17]. The copious amount of gel could help in minimising the transducer pressure during the entire acquisition. This is not always possible, as the size and curvature of the leg can influence the amount of acoustic streaming and visibility of the entire muscle border. To date, no investigation has reported the errors introduced when applying 3DfUS on the MG in a routine setting. Moreover, the reliability is yet to be evaluated in pathological populations, where the muscle borders may appear less defined, such as in SCP [16]. This crucial step is needed to define the potential errors when using 3DfUS for clinical purposes.

After computing a 3D reconstruction, muscles are manually outlined using the reconstructed 2D images, and the corresponding borders are interpolated to generate a 3D mesh of the muscle and tendon. A high number of manually outlined images ensures high accuracy, but results in a time-consuming procedure. To reduce this analysis time and make the method more attractive for clinical use, the validity of using only a selection of the acquired images for manual segmentation should be further explored.

The aim of this investigation is to perform a comprehensive reliability analysis of the 3DfUS technique for acquiring and processing muscle volume, length and echo-intensity (EI) of the MG in TD and SCP children, in a clinically applicable manner. In addition, a gradually simplified procedure will be undertaken to determine the optimized linear density of manual segmentations required to accurately compute muscle volume and EI. It is hypothesised that the data acquisition stage introduces more errors than that of data processing, that the measurement errors for morphological muscle properties are lower than the expected differences between pathological and healthy muscles and that a limited number of muscle border segmentations is sufficient to estimate volume and EI.

2. Materials and methods

2.1. Hardware

A conventional 2D US machine with a linear transducer (59 mm field of view) was used for recording stacks of images (HL9.0/60/128Z, Telemed EchoBlaster 128 Ext-1Z system, Lithuania). The US machine was combined with a portable optical motion tracking system (3 integrated cameras and a 1 mm resolution, Opti-track NaturalPoint, USA) to acquire the pose of four passive markers rigidly affixed to a custom plastic sheath mounted on the US transducer [11]. A trigger (US as master) was used to synchronise the motion-tracking signal with the US signal.

2.2. Acquisition procedure

The MG muscle and Achilles tendon (AT) of 10 TD (5 male; 5 female, age 9.1 ± 3.1 years; body mass 29.4 ± 12.6 Kg) and 10 SCP children (6 male; 4 female, age 11.8 ± 3.1 years; body mass 37.7 ± 17.3 Kg) were assessed. For the acquisition the participant

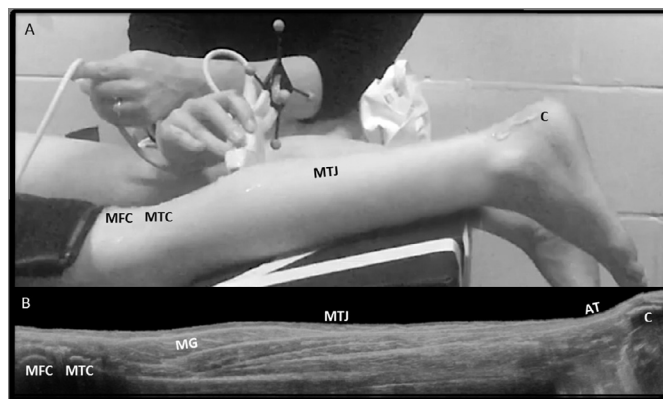


Fig. 1. (A) The experimental set-up for data acquisition and (B) an example of the sagittal view in the 3D data set. The medial gastrocnemius (MG) and Achilles tendon (AT) are visible, together with the medio-femoral condyle (MFC), the medial-tibial condyle (MTC), the muscle tendon junction (MTJ) and the calcaneus (C).

was positioned prone on a plinth with a fixated thigh, knee flexion and a resting ankle angle (Fig. 1A). The most affected leg in SCP children was acquired, whereas a leg was chosen at random for the TD children. The same acquirer, for each child, performed an additional acquisition. On a subgroup of 5 TD and 4 SCP children, a second acquirer performed a further additional acquisition. The US transducer was moved over the skin approximately at a constant velocity, while recording images at 30 images per second. Each participant was asked to lie still during data recording since the motion of the lower leg was not tracked. In cases of muscle contraction or movement of the leg, the acquisition was repeated. The US acquisition parameters were kept constant throughout the investigations (frequency, 10 MHz; depth, 5 cm; focus, 1.8–2.8 cm; gain, 46%, dynamic range, 44 dB and unaltered time-gain compensation). Copious amounts of acoustic streaming gel were used. Acquisitions varied between 30 and 45 s according to the length of the muscle-tendon unit. The US images were recorded from above the posterior aspect of the knee to the distal end of the calcaneus, enabling complete visualisation of the MG and AT (Fig. 1B). As visualisation of the proximal insertion of the MG is challenging, the most superficial aspect of the medial tibial condyle was chosen as the proximal convention [18]. The insertion of the AT was defined as the most proximal point on the calcaneus where the AT first makes contact, whilst the most distal point joining the MG and AT was also chosen as landmark [19].

2.3. Data processing

An in-house open-source software library (github.com/u0078867/Py3DFreeHandUS) developed in Python 2.7 (www.python.org) was applied to process the data acquired from the US and motion tracking systems [11]. This software allocates each of the US images in a 3D space, providing the corresponding 3D data set. According to the real dimension of the pixels in the US images, as well as their total number during the known length of a scan, the data set resolution was 0.5 mm longitudinally and 0.17 mm transversely. In a custom workflow developed in MeVis-Lab (www.mevislab.de), the 3D reconstructed MG was visualised in the transverse plane and the muscle border manually outlined. An algorithm [20] using linear interpolation between the outlined borders was then applied. This procedure enabled visualisation of the 3D rendering and computation of the corresponding volume (see supplementary material). For each processed image, the mean EI (expressed in a grey-scale of 256 values) within the segmentation was computed and then averaged to obtain the mean EI throughout the muscle.

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