Measurements of muscle morphology and composition with ultrasound and MRI.

Adam Shortland PhD
Consultant Clinical Scientist
Guy’s & St Thomas’ NHS Foundation Trust
King’s Healthcare Partners
Adam.shortland@gstt.nhs.uk
Outline

• Gross muscle morphology and muscle function.
• The physics of ultrasound.
  – B-mode, Doppler, Elastography.
• The physics of MRI.
  – Anatomical, Diffusion weighted, Dixon (fat imaging).
• Measurements of muscle morphology in typically developing individuals and individuals with CP (cross-sectional studies).
• Measurements of muscle composition in typically developing individuals and individuals with CP.
• Dynamic measurements with ultrasound – insights into the passive and active characteristics of muscle and tendon.
Muscle design – series and parallel.
The sarcomere

3.5 $\lambda m$

FORCE

LENGTH
The sarcomere
The sarcomere
The sarcomere
The sarcomere

2.4 μm
The sarcomere
The sarcomere

FORCE

LENGTH

1.5 \mu m
The sarcomere

FORCE

LENGTH
Gross morphology = sarcomere arrangement

\[ F \propto N_{\text{parallel_sarcomeres}} \]
\[ v \propto N_{\text{serial_sarcomeres}} \]
\[ \text{Range} \propto N_{\text{serial_sarcomeres}} \]
\[ \text{Power} \propto N_{\text{sarcomeres}} \]
Sarcomeres act at an angle
Physiological Cross-Sectional Area

In long muscles with short fibres, there is no anatomical plane that represents the number of sarcomeres in parallel! i.e. one that crosses perpendicular to the line of action to the fibres.
Physiological Cross Sectional Area

\[ PCSA = \frac{V \cdot \cos \theta}{l_f} \]

Powell et al. (1984) JAP
PCSAs of muscles in the lower limb
How do fibres work together to produce muscular forces?
Neurological coupling

Low Threshold → High Threshold
Mechanical Coupling

- ECM forms continuous mechanical support around muscle fibres.
- Much stiffer than the muscle fibres with which it is connected.
- Distribution of tensile load across the muscle.
- Regulation of sarcomere length.
- ECM (perimysium) is continuous with internal and external tendons.
Summary of gross architecture, morphology and structure

• The force-length and force-velocity properties of muscles are reflected in their muscle architecture.

• The regulation of muscle mechanical performance is dependent on motor unit size and speed.

• The transmission of force is dependent on the integrity of the extra-cellular matrix.
Why image muscle?

• We can measure gross muscle morphology and architecture.
• We can measure something of the mechanical properties of the muscles.
• We can measure *operation* of a muscle during a functional task.
How does (B-mode) ultrasound work?

Piezo-electric crystals are electrically excited and produce a packet of high (2-13 MHz) frequency sound.

The wavepackets are partially reflected at surfaces within the tissue.

Acoustic energy incident on the crystal cause an electrical voltage across it.

Reflections from deeper tissues take longer to reach the crystal.
Ultrasound propagation in tissue

• Attenuation
  – Frequency dependent \( A=A_1 M f \)
  – Higher frequencies have lower penetration.

• Reflection
  – Strength of reflected wave depends on differences in impedance between neighbouring tissues.

• Speed \( c \)
  – Air 300 m/s
  – Muscle 1500 m/s
  – Bone 4000 m/s
How does 2D ultrasound work?

Pulses from successive neighbouring crystals form an image.

There is an upper physical limit for the frequency of scans.

\[ PRT = \frac{2 \cdot D}{c} \quad SRT = N \cdot PRT \quad SF = \frac{1}{N \cdot PRT} \]
Ultrasound Live!
3D ultrasound imaging
How Magnetic Resonance Imaging works

Picture to Proton
Summary of Imaging Techniques

• Ultrasound
  – Ultrasound waves are reflected at boundaries of differing acoustic impedance.
  – Fat, blood, muscle, connective tissue present different acoustic impedances.
  – Spatial resolution and imaging depth are affected by transmitted ultrasound frequency.
  – Temporal resolution is affected by depth and the speed of ultrasound in tissue.
Summary of Imaging Techniques

• MRI
  – Hydrogen nuclei spin on their axis.
  – When magnetised they produce a lateral and longitudinal oscillating magnetic moment.
  – Application of a radiofrequency pulse changes the net longitudinal and lateral magnetisations.
  – Pulse sequences emphasise the relaxation of the lateral or longitudinal components.
  – In different biological materials hydrogen nuclei have
  – Magnetic gradients allow the localisation according to the frequency of precession.
Application I – measurement of fascicle length (ultrasound)

Normalised fascicle length

![Bar chart showing normalised fascicle length for different muscles (MG, LG, TA, VM, RF)].

Legend:
- norm
- CP

Values across muscles:
- MG: 0.4
- LG: 0.4
- TA: 0.6
- VM: 1.4
- RF: 1.1
Application II – measurement of muscle volume (3DUS/MRI)

3D ultrasound study – 6-22 years 26TD, 26CP

10 TD (darker), 10CP (lighter)
3DUS (solid), MRI (striped)
Muscle growth and body growth

\[
y = 1.802x - 11.36
R^2 = 0.76
\]

\[
y = 1.377x - 13.74
R^2 = 0.550
\]

\[
y = 1.610x - 16.17
R^2 = 0.828
\]

\[
y = 0.738x + 1.147
R^2 = 0.292
\]

\[
y = 6.758x - 119.1
R^2 = 0.866
\]

\[
y = 3.081x - 4.244
R^2 = 0.399
\]

\[
y = 2.462x - 25.38
R^2 = 0.811
\]

\[
y = 1.474x - 10.93
R^2 = 0.340
\]
Application III – measurement of muscle composition

% Intramuscular fat

Muscle

MG
LG
SOL
TA
TP

TD
BSCP
Application IV – dynamic performance of muscle

*In vivo* behaviour of human muscle tendon during walking

Tetsuo Fukunaga, Keitaro Kubo, Yasuo Kawakami, Senshi Fukashiro, Hiroaki Kanehisa and Constantinos N. Maganaris*
- Fascicles maintain near-isometric length in single support.
- Tendon stretches during single support and recoils during push-off.
- Passive structures (tendon) perform most of the positive mechanical work which reduces the metabolic cost of muscle contractions.
The following subjects were recruited:

- Eight typically developing children (mean age, 10 ± 2 years)
- Eight independently ambulant children with spastic CP with an equinus gait pattern (mean age, 9 ± 2 years)

- TD children: normal heel-toe and voluntary toe walking
- Children with spastic CP: normal toe-walking gait
Methods

- MTU length was modelled using knee and ankle joint kinematics (Eames et al, 1997)
- Ultrasound probe (with marker cluster) is placed over the distal aspect of the MG (MTJ)
- Tendon length estimated as distance between MTJ and the heel marker (insertion point of tendon in the calcaneus)
- Muscle belly length = MTU length – Tendon Length
Results

Muscle Belly Length Changes

% Change in Length

% Gait Cycle

Muscle Belly Length Changes

Adult Normal Walking

TD Children Normal Walking

CP Children

SWING

STANCE SWING

Single Support

TD Children Normal Walking

% Change in Length

% Gait Cycle

Results
Results

Muscle Belly Length Changes

% Gait Cycle
% Change in Length
Muscle Belly Length Changes
Adult
Normal
Walking
TD Children
Normal
Walking
CP Children

0 20 40 60 80
-5
-3
-1
1
3

Single Support
STANCE
SWING

TD Children
Normal Walking
CP Children

% Change in Length
% Gait Cycle

0 20 40 60 80 100
-6
-4
-2
0
2

Results
Is toe walking the cause of eccentric muscle contractions in children with spastic CP?
Heel-toe and toe walking

TD Children Muscle Belly Length Changes

STANCE SWING

Single Support

Heel-toe and toe walking
Summary

• Muscle weakness is a feature of spastic CP and other upper motor neurone conditions.

• A part of that weakness is due to structural changes in the muscles.

• Muscles and tendons have a beautiful interaction in walking but in children with CP this interaction is altered and muscle bellies may be exposed to eccentric lengthening.
Pros & Cons of Imaging

• Pros
  – Non-invasive; quantitative; repeatable, representative; unambiguous, technically achievable in the clinical environment.

• Cons
  – Limited resolution, limited functional information, ambiguous(!).
Muscle Imaging Futures

- Routine implementation
- Portable 3D systems
- Elastography
Key references


