Anatomically-Based, Subject-Specific Modelling of Lower Limb Motion During Gait

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Abstract

Musculoskeletal models provide insights into muscle structures, and allow for investigations of muscle function during walking based on data from gait analysis. The function of muscles during walking is of special interest in a clinical context if musculoskeletal impairments result in pathological gait. Skeletal muscles in clinical gait analysis have commonly been modelled as series of straight-line segments with no consideration for their 3D architecture. However, experimental and computational results suggest that muscle function is predetermined by anatomical features such as cross-sectional areas and fibre lengths. The validity of straight-line models in gait analysis has been disputed, especially for muscles with complex geometries and broad areas of attachment. The present PhD study has built on a combined effort between the Auckland Bioengineering Institute and the Department of Surgery, University of Auckland, for introducing anatomically-based, subject-specific modelling techniques into clinical gait analysis. In particular, the potential use of anatomically-based models in research related to Cerebral Palsy (CP) was explored. Theoretical background knowledge needed to be acquired in three areas in order to reach this goal: (i) anatomically-based, subject-specific modelling, (ii) clinical gait analysis and (iii) finite deformation of soft-tissue muscle models. The outcome of the present work has demonstrated that muscle volumes and muscle lengths in the lower limbs of children with CP are significantly altered compared to typically developing children, that the Host Mesh Fitting technique provides a valid and efficient method for deriving muscle soft-tissue deformations based on kinematic data from gait analysis, that the calculation of muscle-tendon lengths during walking is significantly affected by errors from optical motion capture and that interactive, web-based visualisation of musculoskeletal models could become a beneficial resource in the teaching of gait. At this stage, the application of anatomically-based, subject-specific models to clinical gait analysis is still considered visionary, requiring an interdisciplinary research effort for further advancing modelling and measurement techniques. Despite remaining challenges, the present work has highlighted the potential of anatomically-based, subject-specific modelling for assisting in the assessment and management of children with CP, and is considered the first step towards the next generation of musculoskeletal models in gait research.

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Half way through my studies, a senior researcher said to me: "You need to be stubborn to finish a PhD". It was certainly not only stubbornness that helped me through the present work but also the personal support and encouragement from my supervisors, work colleagues, family and friends; and the financial support from various funding organisations.

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Recently, another wise person said to me: “You need to be patient to catch the big waves.” If I had to dedicate this work to anything, it would need to be the sea. My deep passion for windsurfing brought me to New Zealand, and my mental and physical escapes into the surf have kept me moving forward. At this stage, I am patiently looking forward to the bigger waves to come, both in my personal and my professional life.

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$\mathbf{u}_i$	Spatial position of node i
Φ_1, Φ_2	Linear Lagrange interpolation functions
ξ	Normalised element coordinates
Ψ_1^0, Ψ_1^1, Ψ_2^0, Ψ_2^1	Cubic Hermite interpolation functions
$\mathcal{F}$	Face Fitting objective function
$\mathcal{H}$	Host Mesh Fitting objective function
$\mathbf{T}$	4×4 transformation matrix
$\mathbf{R}$	3×3 rotation matrix
$\mathbf{t}$	3×1 translation vector
ψ, θ, ϕ	Cardan angles
α, β, γ	Joint angles
$\mathcal{D}$	Direct Least-Squares Method objective function
$\mathbf{F}$	Deformation gradient tensor
$\mathbf{U}$	Right symmetric stretch tensor
$\mathbf{v}$	Left symmetric stretch tensor
$\mathbf{C}$	Right Cauchy-Green strain tensor
$\mathbf{b}$	Left Cauchy-Green strain tensor
$\delta\omega$	Virtual work of forces acting on a body
σ	Cauchy stress tensor
Ψ	Strain-energy density function
$c_{1,2}$	Mooney-Rivlin parameters

$\mathcal{V}$	Volume of Finite Element Mesh
Δf	Standard deviation (error) in variable f
$\mathbf{m}_i^g$	Global coordinates of muscle attachment point i
l	Muscle-tendon length
$\mathcal{S}$	Singular Value Decomposition objective function

List of Acronyms

ABI	Auckland Bioengineering Institute
CP	Cerebral Palsy
CT	Computer Tomography
DICOM	Digital Imaging and Communications in Medicine
DOF	Degree(s) of Freedom
FE	Finite Element
FF	Face Fitting
GMFC	Gross Motor Function Classification
GUI	Graphical User Interface
HMF	Host Mesh Fitting
ISB	International Society of Biomechanics
IUPS	International Union of Physiological Sciencies
MRI	Magnetic Resonance Imaging
RMS	Root Mean Squared
SD	Standard Deviation
STA	Soft Tissue Artefact(s)
VRML	Virtual Reality Modeling Language