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The role of biomechanics in orthopedic and neurological rehabilitation

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Movement is fundamental to human well-being, function and participation in work and leisure activities. As a result, regaining optimal movement abilities and independence frequently become central foci of rehabilitation programs developed for individuals recovering from serious orthopedic and neurologic injuries. Further, preventing additional injury to the locomotor system becomes essential for effective long-term management of chronic medical conditions such as tendon dysfunction and diabetes. The primary aim of this perspective is to illustrate the role of biomechanics in orthopedics, musculoskeletal and neurological rehabilitation. Specifically, this paper discusses selected examples, ranging from the tissue to whole body biomechanics level, that highlight how scientific evidence from the theoretical and applied sciences have merged to address common and sometimes unique clinical problems.

Key words: biomechanics, orthopedics, neurological rehabilitation

1. Introduction

An essential component of human well-being, function and participation in work and leisure activities is the ability to move efficiently and without pain. Curiosity, regarding how animals and people move, led to the development of the science of biomechanics. Human misfortune, either biological of self-inflicted, has necessitated a growing need for orthopedic and rehabilitation sciences.

The basic and applied disciplines influencing orthopedics and rehabilitation have experienced tremendous growth since their inception and this has resulted in improved clinical care. As evidenced over the last decade, contributions from one field (e.g., signal analysis and imaging) have fundamentally influenced growth and application in other disciplines (e.g., tissue and whole body biomechanics as they relate to management of tendon degeneration). This merging of expertise has been essential to improve the management and outcomes of individuals living with chronic medical conditions and disabilities.

The primary aim of this perspective is to illustrate the role of biomechanics in orthopedics, musculoskeletal rehabilitation and neurological rehabilitation. Included are examples ranging from the tissue to whole body level. A secondary goal of this work is to propose a framework for studying movement strategies in persons with musculoskeletal or neurological disorders and to demonstrate how this framework can be applied to select questions and hypotheses.

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1.1. Historical biomechanics in orthopedics, musculoskeletal rehabilitation and neurological rehabilitation

Biomechanics, the science in pursuit of understanding the underpinning principles of movement, is a field that has a very long history. It was described in ancient Chinese and Greek literature as early as 400–500 BC. The foundation for biomechanics, however, was laid during a period between the 1500s and 1700s by renowned contributors, such as da Vinci, Galileo, Borelli, Hooke and Newton [1]. During the 1940s and 1950s, pioneering work of musculoskeletal biomechanics was performed by legends such as Eadweard Muybridge, Arthur Steindler, Verne T. Inman, Henry R. Lister and A.H. Hirsch. Formal, more extensive incorporation of biomechanical principles into the curriculum for orthopedic surgeons, therapists and athletic trainers occurred during the 1960s and 1970s. Since then, the field of orthopedic biomechanics has blossomed. Significant publications related to bone, articular cartilage, soft tissue, extremity, spine and locomotion have expanded the role of biomechanics in clinical decision making. Mathematical modelling has enabled testing of hypotheses that currently cannot be easily tested in vitro or in vivo [2], [3]. Improved engineering design of orthopedic implants has led to longer lasting and more durable prostheses.

The advent of hardware with greater precision as well as software that more efficiently processes large quantities of data has enabled performance of experiments yielding more comprehensive analysis of joint kinematics and tissue function. The findings from this work have increased the understanding of movement control in subjects without pathology during a variety of tasks, including walking, running, exercising, and wheelchair propulsion, and provide a framework for studying movement in the presence of pathology [2], [4]–[6]. Here too, sound hypotheses need to precede experimentation.

Understanding the biomechanical deficits or movement pattern alterations in the presence of a known pathology provides the foundation for developing sound interventions. Returning to a pre-morbid level of work and leisure activities following disease or trauma is termed functional restoration. Orthopedic surgery and physical rehabilitation both seek to functionally restore an individual and their interventions strongly rely on a biomechanical framework for therapeutic design and execution. Surgery with the "do only what is absolutely necessary" context uses a simple static construct to design an intervention and a patient's post-surgical response as means of clinical validation. The first recorded attempt at vertebral stabilization in surgical literature used wires wrapped around adjacent spinous processes in a case of fracture dislocation [7]. Since this introduction, spinal stabilization techniques have been applied to the treatment of spinal tuberculosis, scoliosis, and pain associated with degenerative disorders, which accounts for ~75% of cases appropriate for surgery today [8]. Surgical methodology for restoring spine stability has evolved over the course of a century with innovations in the materials used for grafting, fixation, and implantation procedures [9]. Technology had progressed to the point that all instances of the word "fusion" in the 2004 AMA Current Procedural Terminology coding manual were replaced with the term "arthrodesis" (from Greek meaning joint binding together), which encompasses the array of spine stabilization systems from rigid to flexible.

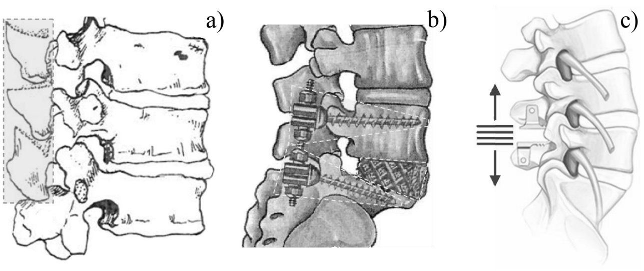

Fig. 1. Historical perspective of surgical inervertebral fusions. Left: posterior fusion only, spinous processes are cut and hinged (Hibbs, 1991). Center: anterior cage and posterior screws (Hodgson & Stock, *BJS* 1956). Right: interspinous dynamic implant, Coflex^{TM} 2008 (Wilke et al. 2008)

An abridged historical perspective of spinal arthrodesis is presented in figure 1. As illustrated in figure 1a, the posterior fusion only created a posterior fulcrum and if the segment was excessively loaded into extension, a secondary instability at that site was often formed, contributing to the return of symptoms. In response to that clinical observation, the inter-body fusion, called "cage", was implemented (figure 1b). The frequency of same-as-surgery instabilities has decreased, but the neighbouring segment syndrome became more prevalent. This suggested that fusion, though often relieving the patient's symptoms post-operatively, was not the optimal solution for the patient's long-term problems. To retain inter-segmental mobility, while providing control of motion, dynamic systems have entered surgical practice (figure 1c). Though conceptually interesting, the true assessment is lacking, as clinical outcome data are still limited. Ultimately, building an understanding of the biomechanical deficits that are either associated with, or may lead to, pathology requires a conceptual framework for biomechanical analysis.

1.2. Conceptual framework for biomechanical analysis of the musculoskeletal system

In the past 10 years, our collaborative research has focused on the biomechanics of the neuromusculoskeletal system, with a particular emphasis on the lower extremities and the lumbar spine. Thorough biomechanical investigations offer a window into human performance. However, the approach to studying motion may vary between laboratories and among investigators. Our conceptual framework for studying human motion in health and disease is multilevel (i.e., whole body, joint and tissue; figure 2). The particular question or the body region of study may require a particular entry into the multi-level system of analyses. Interestingly, in certain disease conditions, such as tendinopathies, not only is the multilevel approach essential but also, knowing the lesion (e.g., Achilles tendon) is useful in hypothesizing the relationships between levels of analyses and perhaps even identifying the portal for a successful intervention. Collaboration with the healthcare community and development of clinical trials allows for the testing of these hypotheses through therapeutic interventions. On the other hand, when the analyses begin from the whole body end of the continuum (e.g., center of mass energetics) and move towards the level of muscle-tendon dynamics, then the motor behaviours can be captured and analyzed globally, without presumptions of a specific pathology. That approach may prove to be essential when the pathology is not well defined or the lesion is systemic or originates in the central nervous system.

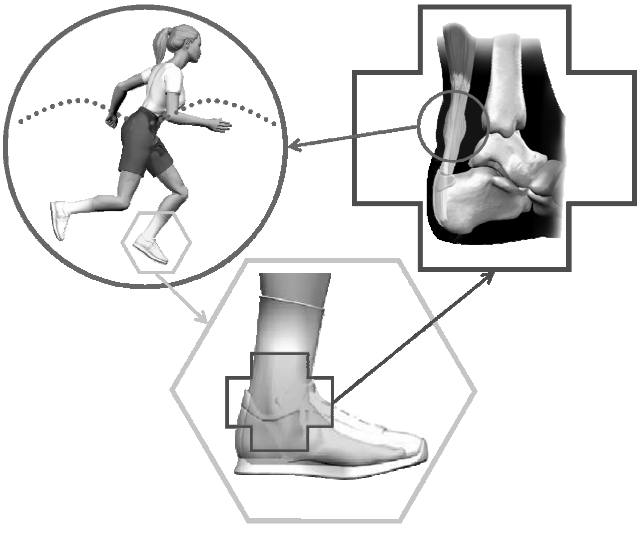

Fig. 2. An example of multilevel biomechanical analyses exploring the relations between whole body (center of mass), joint (ankle joint) and tissue (Achilles tendon)

Though physiologically inseparable, rehabilitation of the neuromusculoskeletal system varies, depending on the location of a known or inferred lesion (i.e., peripheral, systemic or central). Perhaps owing to these differences, orthopedic and neurological rehabilitation have distinct characteristics. As the clinical presentations and questions vary, the scientific hypotheses will differ and the approach to testing them may diverge as well. Here we present examples of the contemporary role of biomechanics in orthopedic and neurological rehabilitation.

2. Biomechanics in rehabilitation

Over the past quarter century, substantial research has focused on musculoskeletal biomechanics. As the number of older adults rapidly increases, so has concern about how to manage conditions endemic to this population such as osteoarthritis of the hip and knee. For younger active adults, areas garnering considerable research focus have included management of patellofemoral disorders as well as prevention or subsequent repair of anterior cruciate ligament ruptures. An area less studied, but certainly not of lesser importance, are movement strategies in persons with lower extremity tendinopathies. Among the most common lower extremity tendinopathies are Achilles, Tibialis Posterior and Patellar.

Tendinopathy is a degenerative condition of tendons associated with periods of debilitating pain, significantly affecting function, activity level and participation at work and leisure. Here, we purport that the clinical presentation of tendinopathy, due to its chronic nature, is not just a painful tendon. In the following section, we will propose and illustrate that pathology is associated with changes in morphological and mechanical properties of tendons and that these changes are reflected in altered joint mechanics. Furthermore, we will provide evidence that at the "whole body level", the human adapts stiffness strategies depending on whether the task is unipedal (hopping) or bipedal (running). The framework for this biomechanical argument will follow that presented earlier in figure 2. Finally, within this framework we will not only present existing, but also propose new directions of rehabilitative strategies for tendinopathies. However, before we discuss the pathological tendon we will briefly examine the normal morphology, kinesiology and biomechanics of the Achilles tendon.

2.1. Achilles tendon: morphology and functional kinesiology

The triceps surae, the muscles attached to the Achilles tendon, are the strongest plantar flexors of the foot. The muscle group is also capable of flexing the knee, and because it also passes the ankle and subtalar joints it is considered a multi-joint muscle group. The physiological cross sectional area (PCSA) of the triceps surae constitutes 77% of the total PCSA of foot plantar flexors. Furthermore, the PCSA of the plantar flexors are 12 times larger than PCSA of dorsiflexors [10]. The ratio of cross sectional area of the triceps surae to its tendon is higher than 15:1 which is surpassed only by the quadriceps femoris. The merging of the tendinous portion of the gastrocnemius and soleus muscles forms this sheet-less tendon. The fibers of the Achilles tendon spiral through up to 60 degrees during its descent such that the fibers that lie medially in the proximal portion become posterior distally [11]. In this way, elongation and elastic recoil within the tendon are possible, and stored energy can be released during the pre-swing period of locomotion [12]. Also, this stored energy allows the generation of higher shortening velocities and greater instantaneous muscle power than could be achieved by contraction of the triceps surae alone [12].

With each successive step, repetitive activation of the gastrocnemius and soleus is accompanied by strain on the Achilles tendon. KOMI et al. demonstrated that the in vivo force load on the Achilles tendon could be up to 12.5 times body weight during jumping [13]. Electromyographic (EMG) studies have shown very high amplitude (75% of EMG observed during maximum voluntary contraction) activity in the gastrocnemius and soleus muscles during terminal stance to provide tibial stability in the presence of a large external dorsiflexion moment during walking [14] and running [15].

Two hypothesized functional causes of achillodynia (painful triceps surae tendon) are foot overpronation and gastrocnemius-soleus insufficiency. Functional overpronation occurs in 55% of runners, a group more often afflicted with achillodynia [16]. The excess pronation causes a "whipping" action of the Achilles tendon and vascular blanching of the mid-portion due to conflicting internal and external rotatory forces imparted to the tibia by simultaneous foot pronation and knee extension. This is an example of tendon loading that does not follow the direction of collagen fiber orientation (superior–inferior). When this sheer load is superimposed on the directional load, the tendon fibers may experience overload.

Variations in movement patterns between injured and non-injured runners may contribute to development of achillodynia. A study of Achilles tendonitis in a group of recreational and competitive runners revealed that the injured had a significantly higher arch and larger inversion angle at initial contact, which resulted in a compensatory overpronation and a "mistiming" of the pronation phase during stance phase or running [17]. ARNDT et al. demonstrated asymmetrical tensile forces in the cadaveric Achilles tendon, with lateral force significantly higher than medial force when either gastrocnemius or all three components of the triceps surae were loaded [18]. The asymmetric load may be a factor contributing to Achilles tendon injury, especially in activities such as long distance running, jumping, sprinting, or "cutting" (rapid change in direction), which require recruitment of the entire triceps surae. Furthermore, higher lateral forces with triceps surae recruitment may predispose the foot to pronation, adding to the conflicting internal and external rotatory forces acting on the tibia and foot.

Gastrocnemius-soleus insufficiency, often associated with decreased length and/or strength, is the second functional factor associated with achillodynia. SMART et al. showed that 37% of runners had gastrocnemius-soleus insufficiency [16]. Others have observed that in runners with achillodynia the injured limb had significantly lower concentric and eccentric plantar flexion strength when compared to the non-injured side [19], [20]. However, this difference in strength likely reflects discomfort experienced by the subjects during maximal effort strength testing.

2.2. Degenerated Achilles tendon: composition, micro- and macromorphology and mechanical properties

Tendon degeneration is evident on several levels. Its primary composition of collagen and elastin embedded in a matrix of proteoglycans and water is altered. Specifically, the newly produced collagen in the presence of tendinopathy has a higher percentage of weaker collagen Type III instead of primary collagen Type I. Furthermore, the collagen bundle architecture has lost its systematic parallel arrangement along the length of the tendon [21], [22]. It develops a disorganized "spaghetti like" appearance that presents itself as a hypoechoic (darker) area within the tendon [23]. This altered collagen bundle organization can be quantified using linear discriminant analyses (LDA) of the FFT (Fast Fourier Transform) of an image captured ultrasonographically [24]. Moreover, especially in the lower extremity, pathology triggers hyper-cellularity, which in turn produces more extracellular matrix resulting in a thicker (i.e., larger cross-sectional area) tendon. In the Achilles tendon, the broadening is pronounced in mid-substance producing focal thickening (figure 3). In addition to the enlargement, the tendon's mechanical properties may be altered due to a loss in the hierarchical arrangement of collagen fibers and stabilizing molecular cross-links [25]. Often not accounted for in the biomechanical analyses are the mechanical consequences of neovascularization. They are direct, that is neo-vessels are formed of weaker collagen, and indirect, that is the tissue atrophies because of lesser functional loading in the presence of neovascularization. The second can be explained by an in-growth of free nerve endings accompanying the angiofibroblastic activity, producing pain and behavioural avoidance of activity, and hence decreased tissue loading.

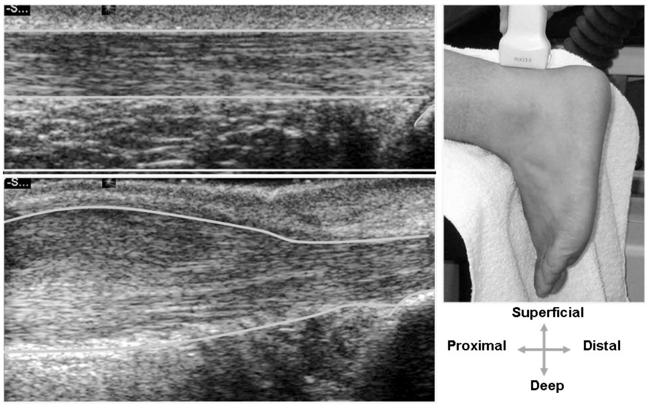

Fig. 3. Ultrasonographic images of Achilles tendons; healthy – top image, degenerated – bottom image. The right insert illustrates the method of image acquisition

In their seminal work titled *Tendinopathy alters mechanical and material properties of the Achilles tendon*, ARYA and KULIG clearly identified that degenerated tendons have diminished mechanical and material properties as compared to those in asymptomatic gender and age matched controls [26]. The history of symptoms and ultrasonography confirmed tendons with tendinopathy. Worth noting is that the subjects in this study did not report symptoms during testing, hence at least at the time of testing pain did not interfere with maximal effort plantar flexion. That does not preclude other more permanent central inhibitory mechanisms from being present. The tendinopathic tendons had an area of hypoechocity and focal thickening on ultrasonographic images. Furthermore, the tendinopathic tendons had a larger cross-sectional area, that is, they were thicker. The tendinopathic tendons had higher strain (%). This in vivo confirmation of pathological tendons becoming less stiff and more compliant further suggests that the material properties are being altered as discussed earlier, tissue breakdown is exceeding the rate of repair.

2.3. Inter-segmental dynamics in the presence of tendinopathy

Unresolved patient challenges often provide the basis for clinically-relevant biomechanical studies. A strong understanding of normal and abnormal biomechanical movement patterns provides the framework for designing experiments and testing scientifically-sound hypotheses. For example, tendinopathies are often long-standing with periods of significant exacerbation followed by periods of dormant symptoms. As the symptoms wax and wane, the tendon's morphology and mechanical properties likely remain pathological. The continued pathology is relevant to the patient, clinician and researcher. The patient and clinician need to be cognizant that the tendon remains vulnerable to trauma. The researcher has a window of opportunity to study the movement strategies employed by a patient without the interference of pain.

To explore the question of whether intersegmental mechanics are altered in the presence of longstanding tendinopathy, we studied running in a skilled runner [27]. We designed two cascading experiments. The first focused on establishing the mechanical properties of bilateral tendons by synchronized recordings of the plantar flexor torque (dynamometry) and displacement of aponeurosis of the medial gastrocnemius (gray scale ultrasonography), followed by appropriate mechanical calculations. The second experiment consisted of repeated running trials in the laboratory to profile the bilateral lower extremity kinematics and kinetics. The prevailing focus of these biomechanical analyses was stiffness. As hypothesized, the involved tendon was less stiff than the non-involved tendon (figure 4, left). During running, the ankle torsional stiffness was lower on the involved side, and the knee torsional stiffness was higher on the involved side (figure 4, center). Interestingly, leg stiffness during running was equal between legs (figure 4, right). Whether the tendinopathic leg up modulated its stiffness or the healthy leg down modulated its stiffness, it is not yet known.

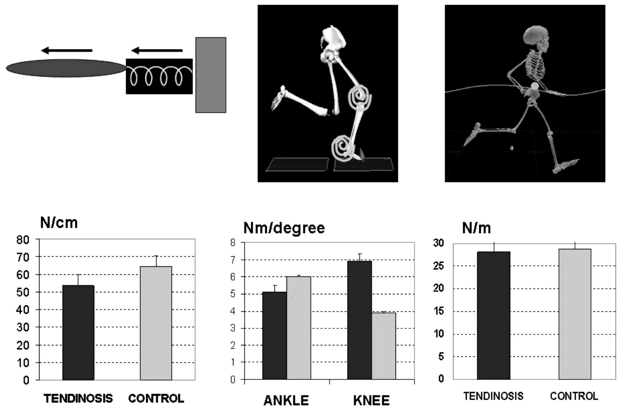

Fig. 4. Stiffness characteristics in a runner with Achilles tendinosis. From left to right: Achilles tendon stiffness measured during isometric plantar-flexion (N/cm), ankle and knee joint torsional stiffness during running (Nm/degree) and leg stiffness during running (N/m). Adapted from Arya and Kulig, 2005

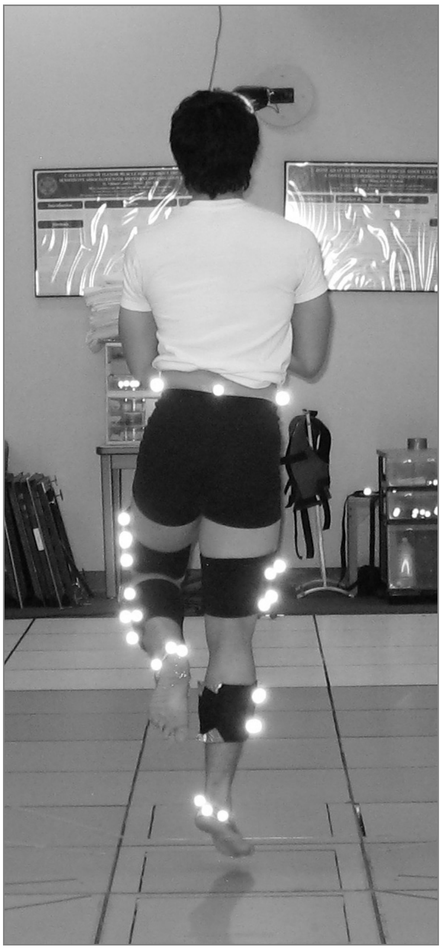

Fig. 5. Subject performing single-legged hopping on a force platform

Unlike running, which requires a bi-pedal forward bound locomotive strategy, hopping is a single-legged activity that can be performed in place. During a hop, the hip, knee and ankle work in concert to accomplish the task of moving the center of mass against gravity. This task requires complex coordination to achieve appropriate torque output from each of the lower extremity joints. These analyses lend themselves to a simplified examination of a mass-spring model, inter-hop variability and support moments. The total support moment is an antigravity measure of the total torque demand experienced by the lower extremity to prevent collapse [28]. It is calculated by summing the net sagittal plane moments of the lower extremity (i.e., ankle, knee, and hip) [29]. We tested 30 active males, 16 of whom had tendinopathy, either at the Achilles or patellar tendon. All performed 20 consecutive hops, while instrumented for biomechanical analyses (figure 5). The percent contribution to total support moment varied between healthy and tendinopathic subjects. Individuals with Achilles tendinopathy demonstrated a significantly lower ankle joint and a higher hip joint contribution to support moment compared to controls (figure 6a). Similarly, individuals with patellar tendinopathy demonstrated a significantly lower knee joint and a higher hip joint contribution to the support moment compared to controls (figure 6b) [30]. Collectively, tendinopathy was related to lower per cent contribution to support moment by the joint associated with pathology. This lower joint contribution was compensated for by a higher per cent contribution of the hip joint to support moment. The observed alteration in the limb kinetic pattern and its implications for functional performance certainly warrant further investigation. Moreover, an exploration of

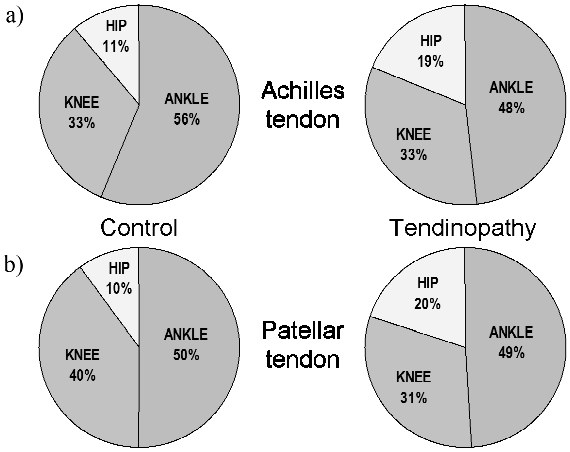

Fig. 6. Individual ankle, knee and hip joint contributions to support moment in controls and individuals with Achilles (a) and patellar (b) tendinopathy. Adapted from Arya et al., 2008

the variances in joint contribution during single-legged and bipedal tasks may shed light on the underlying mechanisms, adaptations and maladaptations of the neuromusculoskeletal system at the peripheral or central levels.

2.4. Rehabilitative strategies for tendinopathies: tissue specific, joint specific or whole body system?

Key, for both clinicians and patients, is the ability to translate these findings into guidelines that ultimately reduce pain and exacerbations and improve function. As illustrated earlier, the biomechanical analyses revealed changes at the tissue, joint and whole body level. Hence the resulting questions are: Should rehabilitative strategies target the tissue or the whole body? Is the degenerated tendon tissue modifiable? Are the altered intersegmental dynamics modifiable, and how? The authors of this perspective would argue that a successful intervention leading to retained functional restoration must carefully assess all impairments, analyze patients within the biomechanical framework, and treat each using a broad based biomechanical and behavioural model [31]. The well-established intervention for tendinopathies is eccentric tendon loading aimed at remodelling the disrupted tendon fibril architecture. This may provide superior results, if whole-body interventions are added to the therapeutic program.

3. Biomechanics in neuro-rehabilitation

In rehabilitation, biomechanical tools and principles provide the underpinnings not only for identifying the presence of movement disorders, but also for developing and assessing the impact of innovative treatment interventions. Biomechanical studies directly influence the independence and quality of life of individuals living with chronic conditions (e.g., multiple sclerosis and diabetes mellitus) as well as those recovering from life-changing medical events such as a stroke, spinal cord injury and traumatic brain injury. The following sections highlight examples of how biomechanical principles and tools guide clinical management of clients with neurological disorders to not only restore function following a catastrophic event, but also to prevent additional medical complications in the presence of chronic conditions (e.g., diabetes).

3.1. Clinical gait studies

Rehabilitation gait laboratories emerged in part to serve the unique needs of those living with the long-term consequences of a physical disability. Simultaneous recording of dynamic kinematic (motion), kinetic (forces) and electromyographic (muscle activity) data quantifies the degree and underlying causes of movement disorders and serves as a basis for treatment planning (figure 7) [14]. During typical gait studies, footswitches are attached to the plantar surface of the shoes or feet to define specific phases of the walking cycle (e.g., initial contact, loading response, or terminal stance). Data recorded from the footswitches are then used to document deviations in timing from normative values (e.g., a prolonged stance phase and/or a shortened single limb support period). Abnormal foot contact patterns (e.g., an initial contact with the forefoot or a drag during swing) also are quantified. While data recorded from footswitches can readily quantify the presence of gait abnormalities, footswitches alone do not define the offending joints or muscles contributing to the gait abnormalities.

Fig. 7. Gait study with simultaneous recording of stride characteristics (in-shoe footswitches), full body kinematics (passive reflective markers), ground reaction forces (embedded forceplates) and lower extremity muscle activity (surface electrodes)

Three-dimensional analysis of joint motion identifies key movement deviations in the sagittal, frontal, and transverse planes during specific gait phases [14]. Kinematic data, although more time-consuming to acquire and process than footswitch information, can further clarify the anatomic regions of pathology. For example, a drag detected with footswitches may arise from multiple sources, including limited knee flexion during initial or alternatively excessive ankle plantar flexion during mid-swing. Kinematic assessment defines the specific joints that move abnormally and, when combined with footswitches, can clarify the phases during which abnormal movements occur.

Force platforms embedded in the walkway surface record ground reaction forces and, when combined with kinematic data, enable calculation of joint moments and power. These latter two variables are frequently used to infer the demand placed on contractile and non-contractile elements involved in moving and stabilizing the limbs.

Dynamic electromyography (EMG) serves an essential role in differentiating primary gait deficits arising from clients' underlying impairments (e.g., the causes of limited knee flexion during swing) from compensatory maneuvers (e.g., circumduction for limb clearance so the individual does not trip) [14]. EMG sensors record the electrical signal produced by a muscle during activation. The specific timing and relative intensity of muscle effort in larger superficial muscles (e.g., vastus lateralis or biceps femoris long head) are often aptly recorded using surface electrodes [32]–[34]. Fine wire electrodes are required to accurately document activity of deeper muscles (e.g., tibialis posterior or flexor digitorum longus) [35]. The issue of cross-talk between muscles should be considered [36]–[39], [35], [40], particularly when muscle atrophy is suspected, as surface electrodes may be susceptible to recording the signal of not only the targeted muscle, but also muscles beneath or adjacent. Once accurate and valid data have been recorded from the targeted muscles, then the knowledge of "normal" spatiotemporal profiles for muscle onsets, cessations and relative intensities is used to guide interpretation of clinical gait EMG recordings [14].

3.2. Clinical gait example: multiple sclerosis

Multiple sclerosis (MS) is a progressive neurological disorder caused by destruction of the myelin sheath that surrounds nerve cell fibers in the brain and spinal cord [41]. The demyelination can lead to slowing or blockage of the signals in the nervous system resulting in multiple symptoms including muscle weakness, spasticity, fatigue, depression, as well as mobility and balance problems. An estimated 250,000 to 350,000 individuals living in the United States have been diagnosed with multiple sclerosis [41].

Following a more than 20 year history of multiple sclerosis with a progressive decline in walking function, the client discussed in this case study was referred to Madonna's Movement and Neurosciences Center to identify underlying causes of her gait challenges and to recommend treatment options. The client reported falling approximately 10 times during the previous year. Bilateral footswitch data, lower extremity kinematics and surface EMG were recorded as the client traversed a 6-meter walkway using a three-wheeled walker (figure 8). The client's self-selected comfortable walking speed was limited to only 6 meters/minute (<10% normal adult walking velocity) due to reductions in both stride length (~50% normal) and cadence (21 steps/minute).

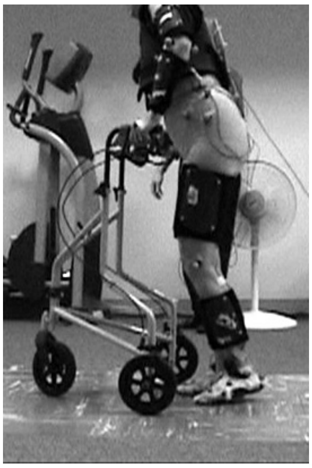

Fig. 8. Client with multiple sclerosis experiences difficulty with foot clearance during initial swing due to limited knee flexion

Observationally, the client exhibited bilateral foot drags, a stiff-legged gait pattern, and excessive dorsiflexion during stance. Footswitches confirmed the presence of the bilateral foot drags (figure 9, lower two tracings). For the purposes of this example, we will limit our focus to identifying underlying causes of the left foot drag. An analysis of the kinematic data revealed that the primary source of the left foot drag was the limited left knee flexion which started during pre-swing and continued through initial swing (figure 10, upper tracing). The foot drag was not arising from excessive plantar flexion as the left ankle was actually postured in excessive dorsiflexion during the first two-thirds of swing (figure 10, lower tracing). Additionally, the hip achieved adequate flexion during mid-swing. An analysis of the EMG data identified that one dynamic contributor to the limited knee flexion was continuous activity of the left vastus lateralis

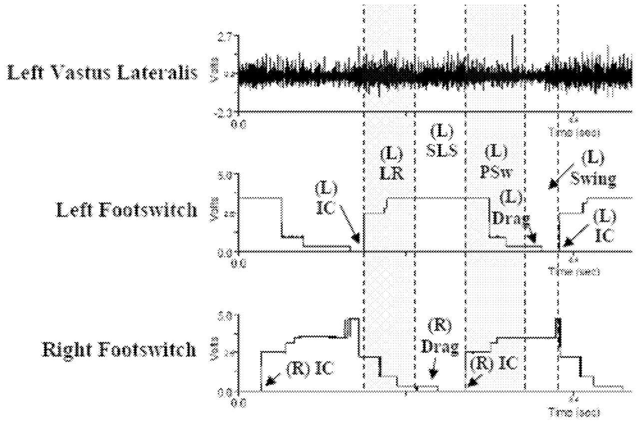

Fig. 9. Footswitch (lower two tracings) and vastus lateralis surface EMG (upper tracing) data recorded simultaneously from a client while walking with a four-wheeled walker. Note the drag occurring at the beginning of swing for both the left and right feet. Vastus lateralis activity was continuous versus demonstrating normal phasic timing (key: L = left; R = right; IC = initial contact; LR = loading response; SLS = single limb support, i.e., mid and terminal stance; PSw = pre-swing).

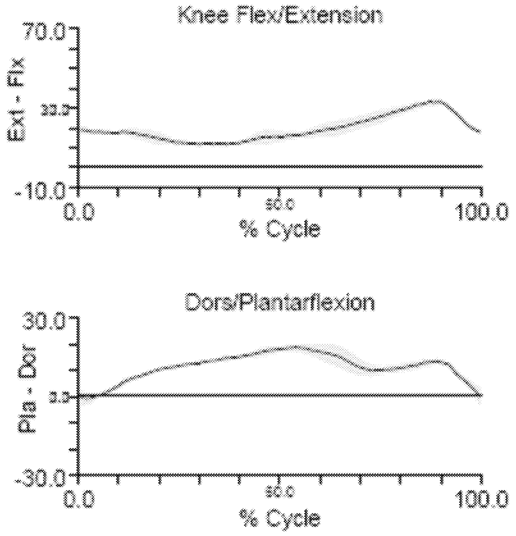

Fig. 10. Three-dimensional motion analysis of the client's left lower extremity reveals excess knee flexion during stance and limited knee flexion during pre-swing and initial swing (upper tracing). The ankle demonstrated excess dorsiflexion throughout stance and swing, with only initial contact demonstrating a neutral posture (key: black line reflects mean data; gray shaded area reflects standard deviation across multiple strides)

(figure 9, upper tracing). The vastus lateralis is normally active primarily during terminal stance and loading response. For this client, the continuous vastus lateralis activity resisted the normal passive and active knee flexion that occurs during pre- and initial swing and contributed to the foot drag. A more comprehensive analysis of the client's bilateral stride characteristics, lower extremity kinematics and EMG was used to guide clinical decision making related to surgical implantation of an intrathecal baclofen pump, lower extremity orthotic management, and a strengthening and conditioning program.

3.3. Biomechanics to guide gait retraining efforts

Specificity of training has often served as a guiding principle as clinicians select treatment interventions to improve movement and function [42], [43]. While a number of training options are available in inpatient and outpatient settings to help clients regain their walking ability (e.g., partial body weight support treadmill training [44]–[48] and robotic gait retraining [49]–[54], clients often face challenges as they make the transition to community-based fitness facilities. Lacking are accessible tools that help them to continue to focus on walking-like movement patterns. An elliptical (cross) trainer is one exercise machine commonly found in fitness facilities. This device is often promoted by manufacturers as having a movement pattern similar to walking; however, the degree of similarity has received only limited attention in published literature. Similarly, the intensity and timing of muscle activation had not been systematically explored. A preliminary kinematic analysis of elliptical training and walking overground revealed that motion patterns between the two activities were similar, except subjects were positioned in greater flexion (i.e., more bent) at the hip, knee and ankle during elliptical training (figure 11) [55]. The coefficient of multiple correlations (CMC) was used to quantify the similarity between motion patterns recorded during elliptical training versus those occurring during overground walking at each joint (CMC values range from 0 = no similarity to 1 = highest similarity) [56]. The motion patterns demonstrated the greatest similarities at the hip (CMC walking vs. elliptical training = 0.88) and knee (CMC walking vs. elliptical training = 0.85), while a more moderate relationship was identified at the ankle (CMC walking vs. elliptical training = 0.43). Similarities in muscle activation patterns between overground walking and elliptical training on a single device also were documented (figure 12) [57]. Further work is underway to identify those elliptical trainers that most closely simulate normal overground walking movement patterns (**work funded, in part, by grant H133G070209 to JMB**).

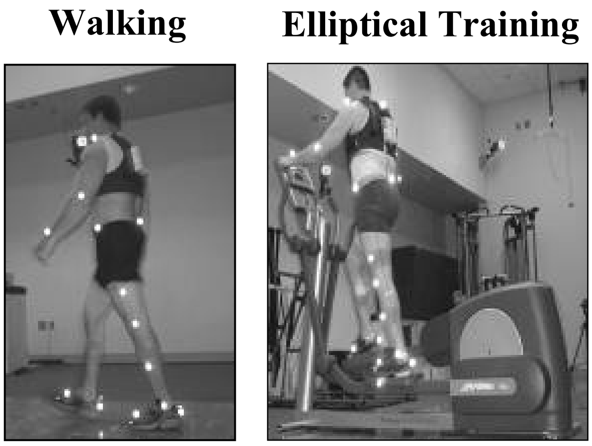

Fig. 11. Kinematic comparison of walking and elliptical training movements provides insights into using elliptical training therapeutically as a tool to help individuals regain walking ability

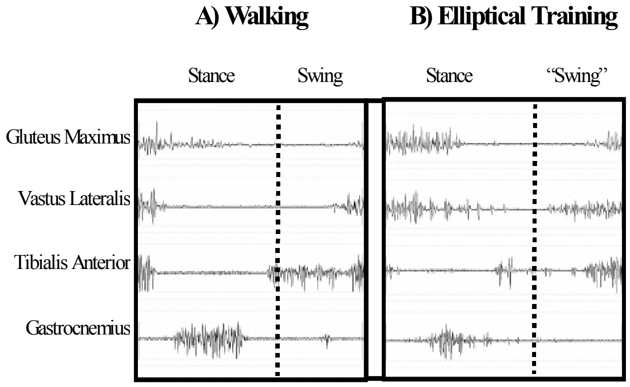

Fig. 12. Comparison of muscle activity recorded using surface electromyography (EMG) during a single cycle of A) overground walking and B) elliptical training for a young adult male. While similarities were observed in the relative phasing of muscles during stance and swing, activity in the gluteus maximus, gluteus medius, and vastus lateralis was prolonged during elliptical training

3.4. Using biomechanics to promote safer exercise opportunities for persons with diabetes

Diabetes mellitus (DM) affects more than 18 million people in the United States and can lead to secondary complications including heart disease, stroke, high blood pressure, blindness, foot ulcers and amputations [58]. Peripheral neuropathy is present in approximately 40% of individuals diagnosed with DM for 10 years [59] and 50% of all individuals who have had DM for 25 years [60]. Individuals with a peripheral *sensory* neuropathy often describe feelings of numbness in their legs [61], [62]. Peripheral neuropathy increases the risk of developing foot ulcers by reducing a person's ability to feel pain in their feet. Another key factor that can contribute to the formation of foot ulcers is high plantar pressure [63], particularly when sensation is diminished. Hence efforts aimed at minimizing foot pressures are essential.

Exercise is often recommended as a central component of health management plans for people with diabetes [64], [65]. One area of growing interest is how to minimize pressure during prolonged periods of weight-bearing cardiovascular exercise. The use of special insoles designed to measure in-shoes pressures provides one biomechanical tool for guiding selection of exercise interventions in persons with and without diabetes mellitus. BURNFIELD et al. [57] measured plantar pressures using the Pedar pressure mapping system (developed by Novel, Inc) as clients performed five cardiovascular exercises commonly available in community-based fitness facilities. It was hypothesized that plantar pressures would vary significantly across the five activities (walking, running, elliptical

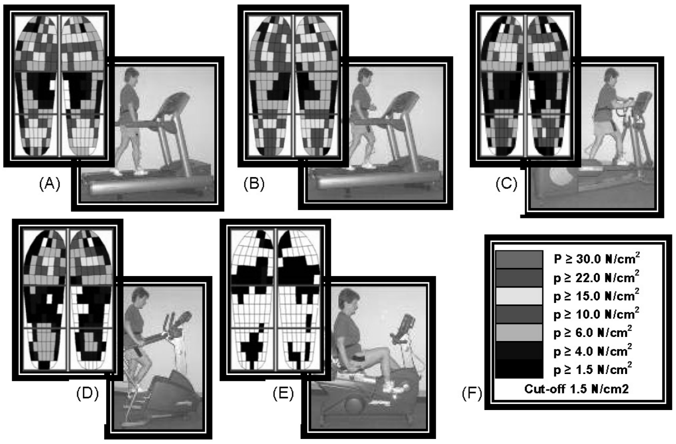

Fig. 13. Exemplar subject performing each exercise and corresponding peak pressure map for: A) treadmill walking; B) treadmill running; C) elliptical training; D) stairclimbing; and E) recumbent biking. F) Legend for pressure maps. These pressure patterns were consistent across all ten subjects. Note: 30.0 and 22.0 N/cm^2 pressures could be potentially harmful for insensate feet

training, stairclimbing and recumbent biking) due in large part to variations in surface contact area (remembering that pressure = force/area). For example, walking and running both include periods of single limb support when body weight is concentrated through a single limb. In contrast, during elliptical training and stairclimbing both feet maintain continuous contact with the ground and the hands often rest lightly on support surfaces. Recumbent biking was expected to register the lowest plantar pressures due to the inclusion of the buttock surface area in addition to the feet and hands. Figure 13 highlights findings from work with older adults without diabetes [57]. Note the relatively high forefoot pressures occurring during walking and running, while pressures during elliptical training and stairclimbing were intermediate. The lowest pressures occurred during recumbent biking.

4. Summary

The primary aim of this perspective was to highlight the essential role of biomechanics in orthopedics, musculoskeletal and neurological rehabilitation. Selected examples, ranging from the tissue (e.g., tendon) to whole body level (e.g., the client with multiple sclerosis), were presented to showcase how scientific evidence from the theoretical and applied sciences have merged to address widespread and sometimes distinct clinical problems. Collectively, these examples point to the critical need for collaboration among biomechanists, clinicians and clients to further expand the understanding of human movement in the presence of pathology. This collaborative approach offers strong opportunities to improve the overall well-being, function and quality of life of individuals impacted by disability and chronic conditions.

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