Special Issue “Orthopaedic and Rehabilitation Engineering”

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Abstract: This paper serves as an editorial preface to a Special Issue on Orthopaedic and Rehabilitation Engineering. The fields of Orthopaedic and Rehabilitation Engineering encompass a variety of topics. Perspectives on a variety of topics in these fields are presented, followed by a brief description of the contributions comprised in this Special Issue.

Keywords: biomechatronics; human motion and posture; mechanical indeterminacies; multi-scale musculoskeletal biomechanics; neuromuscular redundancies; rehabilitation engineering

1. Motion Biomechanics and Postural Stability

Mechanical impedances of joints and limbs in relation to motor control and to the protection of joints and limbs from excessive loads are of great interest for the characterization of motion and of stability [1]. The lower limb is often subjected to excessive loading, which may lead to damage, both in the short term (to bones and muscles [2–4]), and in the long term (to joint cartilage and spinal intervertebral disc [5,6]). The following presents a brief account of the effects encountered by external dynamic loading on the human body.

1.1. Simulation of Impact Loading on the Lower Leg

Impact loading on the human body in vertical free-fall is usually transmitted through the lower limb upward. Studies on the transmission of impact forces in a straight leg applied vertically on the foot toward the hip level was investigated by a two-degree of freedom linear damped-spring model. Foot-ground forces measured during a vertical free-fall and accelerations measured at the level of the greater trochanter served as model input. The model elastic constants and damping coefficients were determined by solving the dynamic equations of the system [7]. In real situations, however, motion is carried out with the active involvement of muscles during joint motion to take advantage of the additional elastic and damping contributing to the attenuation of peak loads resulting from impact. Thus, the role of joint motion was studied during vertical landing of human vertical free-fall in different falling conditions to reveal the parameters which take part in the attenuation of impact forces [8]. The results indicated that joint movements and muscle action play a major role in reducing peak forces during landing from free-fall, suggesting the importance of adequate training to improve pre-programmed nonreflex muscle action, which is necessary in the early phase of impact.

A hopping motion represents a succession of repetitive impact vertical loading on the body through the lower leg. The stiffness and damping profiles of the leg joints during the ground-contact phase of hopping were thus studied by developing a two-dimensional (sagittal plane) jumping model, consisting...
of four linked rigid segments and including the paired feet, shanks, thighs, and the head–arms–trunk segment [9]. The maximal stiffness during the ground-contact phase was found to be in linear correlation with the initial stiffness in each joint, providing support to the pre-activation strategy during the flight phase of hopping.

1.2. Simulation of Rapid Eversion Motion of the Foot and Ankle Sprain

Ankle sprain is a common problem occurring in athletes and in the wide population [10–12]. To simulate sudden eversion motion of the foot relative to the shank, the human subtalar joint was modelled as a quasilinear second-order underdamped system [13]. Motion is applied unexpectedly to provoke full foot eversion motion in a short-enough period of time, so as to avoid activation of the protective peroneal muscles [14]. The effects on the test parameters of weight bearing amount, foot dominance, and protective footwear could be studied. Other studies performed in the plantar-dorsi flexion axis have revealed the in-vivo dynamic properties of the ankle joint [15].

1.3. Upper Limb Navigation during Simultaneous Control of Grasping and Walking

The simultaneous coordination of reaching movement, hand prehension and locomotion has been in the focus of several studies [16–18]. In a reaching motion, it has been shown that distal joints provide the refined adjustment of hand motion, whereas the more proximal ones dominate global navigation of the hand [19,20]. Impedance adjustments during the simultaneous control of grasping and walking under ordinary conditions, as well as when one of the joints is affected, have been studied in attempts to decipher the neuro-muscular strategies employed and the mechanical responses of the arm during certain tasks of manual materials handling [21]. A regressive function was used to express stiffness, including first-order dependence on angle and on angular velocity. The function used for damping included first-order dependence on angular velocity. Redundancies in the numerical solution were eliminated using multicollinearity diagnostic algorithms [22].

1.4. Effects of Muscle Fatigue

It has been shown [5] that muscles act to lower the bending stress on bone and to attenuate the peak dynamic loads that can damage musculoskeletal tissues. Muscle fatigue has also been shown to affect the ability of the human musculoskeletal system to attenuate and dissipate the heel strike induced shock waves for running [23] and for the long march [24]. It has been suggested that when the muscle’s ability to perform is diminished, the cartilage and ligaments become more vulnerable to excess dynamic loading, which, in turn, may increase stiffness. Nevertheless, in direct contrast to experiments on whole body fatigue, localized muscle fatigue was found to cause a decrease in peak tibial acceleration and acceleration slope following impact [23,25]. Further to the increase of impact acceleration with progressing fatigue during running, an imbalance in the contraction of the shank muscles develops. The combination of these two changes hampers the loading balance on the tibia since the bone becomes exposed to excessive bending stresses and to higher risk of stress injury [26].

1.5. Standing Balance

Bipedal standing is an unstable position that necessitates continuous regulation processes, involving periodic contractions of muscles in the lower limbs and trunk. The direct result of this continuously acting stabilizing system is the existence of body sway in the sagittal, coronal, and transversal planes [27]. Toward the quantitative analysis of sway motion, models have been developed for the estimation of the trajectory of the body’s centre of gravity during standing sway, based on the foot-ground reactive forces and centres of pressures as measured bilaterally from two force platforms [28]. This model has further been applied to characterize standing balance activity in groups of hemiparetics and of below-knee amputee subjects [29]. The further development of this model led to the ability to estimate the dynamics of the lower extremities in standing Sway. A three-dimensional, five-segment, four-joint model of the human body
was used to describe postural standing sway dynamics. An inverse kinematics algorithm was thereafter used to evaluate the kinematics of the body segments [30]. Finally, the same inverse kinematics algorithm was extended to provide estimations of dynamic joint torques in hip, knee and ankle during sit-to-stand from two-dimensional kinematic data and foot-ground and thigh-chair reactive forces before and after the seat-off phases [31]. Findings from a study using the same model suggest that smaller hip flexion torque and a prolonged rate of torque production are significant mechanisms that contribute to the disruption of sit-to-stand performance in Parkinson’s patients [32].

2. Functional Electrical Stimulation (FES) of Muscles

The Functional Electrical Stimulation (FES) of muscles is an artificial way of activating muscles (usually, but not solely, skeletal muscles) for functional purposes. FES can be applied either for restoration of lost function or for the augmentation of an existing weakened function. In addition, using transcutaneous electrical nerve stimulation (TENS), somatosensory stimulation can be applied to activate parts of the motor and sensory networks.

2.1. Restoration

FES has been used to induce contractions of impaired muscles, e.g., in spinal cord injury patients as a rehabilitation technique for improving the performance and physical state of spastic paralyzed muscles and for restoring the locomotor abilities of these patients [33,34]. Computer controlled portable stimulators have been developed for the functional activation of paraplegic’s muscles [35]. Apparatuses and systems have been reported for the restoration of standing and walking by combining microcomputer-controlled electrical stimulators and instrumented walkers [36]. When electromyographic (EMG) measurements are required in the presence of FES, the high-magnitude stimulus artefact produced necessitates methods for suppression of this artefact [37].

Two major issues associated with functional electrical stimulation (FES) of paralyzed muscles [38] are: (i) The mechanism of force generation by means of the recruitment of muscle fibres, and (ii) the variation of the muscle force with time as a result of fatigue under sustained stimulation. These issues determine the quality of performance to a great extent. Objective means of monitoring fatigue are essential in cases of lack of sensation due to paralysis. Measured EMG and phosphometabolites profiles (the latter monitored by Magnetic Resonance Spectroscopy, Levy et al. [39]) have been attributed to the fatiguing and recovery processes of the contractile machinery and of the excitation-contraction coupling mechanism [40]. Musculo-tendon modelling and incorporating the fatigue profiles enabled researchers to predict the muscle force profiles in continuous as well as in intermittent stimulation [41–44]. Finally, electromagnetic modelling of FES allowed researchers to predict the current density profiles within the muscle [45,46], effect of stimulating electrode configuration [47,48] and transmembrane potential distribution along a nerve fibre [49,50].

2.2. Force Augmentation by FES

Augmentation of force in partially deficient muscles can be achieved by combining electrical stimulation (ES) with their volitional activation (hybrid activation). However, while the overall torque results from the combination of the volitional and the electrically induced torque components, the exact share between these components is not known. Methods have thus been developed using a computational scheme to extract the volitional EMG envelope from the overall dynamic EMG signal, with the latter serving as an input signal for control purposes and for the evaluation of muscle forces [51]. Using these methods, it was possible to resolve the share between the torque components under isometric static contractions [52] and dynamic contractions [53].

2.3. Somatosensory and Motor Augmentation by TENS

Somatosensory stimulation activates large parts of the motor and sensory networks, both in the contralateral and ipsilateral hemispheres [54,55]. The potential of somatosensory stimulation,
using transcutaneous electrical nerve stimulation (TENS) to serve as a useful complementary therapy in neurorehabilitation, has been investigated with positive results [56,57]. For example, a study by Cuypers et al. [57] examined the long-term effect of TENS on tactile sensitivity in patients with multiple sclerosis (MS). Findings from this study revealed that long-lasting improvement in tactile sensitivity can be induced by means of TENS in MS patients, allowing them to reach comparable levels of sensitivity to those of healthy subjects after chronic (three weeks) repetitive stimulation of the median nerve region. Findings from another study by the same research group using similar TENS protocol to the right abductor pollicis brevis (APB) muscle demonstrated TENS-induced enlargements in cortical motor maps, which were not restricted to the stimulated muscle, but also extended to other hand and forearm muscles in healthy human volunteers [58]. Besides TENS, other somatosensory stimulation methods such as tendon vibration may also be considered [59].

3. Musculoskeletal Interactions

Musculoskeletal interactions in able-bodied and disabled human individuals determine the loading of the body parts, as well as the performance of human motion. Fatigue (either central or peripheral) strongly affects the ability of the musculoskeletal system to protect the bones and joints from impact loading.

3.1. Muscle and Shock Absorption

Apart from their function as joint actuators, muscles also act as active shock absorbers. It has been hypothesized that muscle fatigue can reduce the effect of damping and accelerate the initiation of stress fractures [60]. It has also been shown that, as a result of muscle fatigue, there is an increase in the strain rate (i.e., rate of strain development) in the tibia [61], suggesting that loading of the tibia during running becomes more impulsive as fatigue progresses.

Information about impulsive loading on the bone in walking and/or running can be obtained noninvasively by measuring the transient accelerations on the shank caused by the impacting foot on the ground. Thus, in situations of fatigue or more severe muscle impairment, both functions of the muscle, i.e., the actuator and shock absorber, are hampered, and the following may be expected to take place: (i) Increased transmission of shock loads along the skeleton [23,25,26,62–64]; (ii) loading imbalance on the bones, resulting of increased stresses there [26]; (iii) altered kinematics [62] and (iv) increased risk of overload injuries and of joint degeneration [65,66].

The following questions may then be asked: Are there means to enhance muscle activity so as to increase its protective action under fatigue or other deficient conditions? By electrically stimulating the muscle, can one create the required mechanical environment on the neighbouring bone? Bone and muscle are not only in the same vicinity, thus physically influencing each other, but also functionally coupled together. It has been shown that muscle stimulation can provide a favourable mechanical environment to the bone and bone cells [52,53,67,68].

3.2. Neuromuscular Interactions and Hybrid Activation

In hybrid activation, where volitional self-activation is augmented by electrical stimulation, the resulting force cannot be considered a simple summation of its components due to interactions between them [69]. These interactions may be either of the following types: (i) Short-term, including reflex inhibition of the antagonistic muscles due to electrical stimulation of the agonistic muscles [70], catch-like effects [71], and stimulus rate modulation (if synchronized with the volitional pulse trains); (ii) medium-term effects that can last for minutes after the stimulation pulse train was stopped, including increased twitch forces [72], or enhanced cortico-spinal excitability [73,74]; (iii) long-term changes following prolonged training involving strengthening of the muscle and remodulation of its fibres [75,76]; (iv) long-term effects due to training-induced neuroplastic changes in the corticospinal tract [77].
4. Neuromuscular Redundancies and Mechanical Indeterminacies

A major and interesting question in human biomechanics and kinesiology is how many muscles are required for performing a given motor task. Not less intriguing is the question relating to the number of muscles actually engaged in performing the given motor task. Past work on human locomotion has demonstrated that, taking level walking as an example, no less than 31 muscle groups are engaged in each leg. Electromyograms of the major muscles of the leg during locomotion have been used to show the sequence of muscle activation in the gait cycles [69,78]. It may be argued, however, that the involvement of all the muscles in the abovementioned walking task is not essential, and that the locomotor system is neuro-muscularly redundant, with substantially more acting muscle groups than actually required. Mechanically, the consequence of this redundancy is that the number of unknown internal joint and muscle forces exceeds the number of mechanical equations, rendering the system mechanically indeterminate.

Methods were developed for characterizing the parameters of the major muscle groups controlling the limb joints in motion, with the latter having particular significance in the quantifying of redundancy in coordination [79] and in rehabilitation of locomotion [80]. To lower mechanical indeterminacy in the joints during motion, the system is reduced by grouping the muscles acting in synergism. The joint torques were calculated by inverse dynamics methods from cycling motion data, including kinematics and foot/pedal reaction loads (forces, moments). The mechanical indeterminacy was resolved by applying optimization criteria and the individual muscle torques were parcelled-out from the joint torques [81]. System identification of the individual muscles, part of which were bi-articular, in this nonisometric condition was performed from the relationship between the evaluated force and the measured EMG of each the muscles using both first- and second-order linear transfer functions [82].

5. Optimization of Load Distribution in Artificial Joints and Orthopaedic Implants

Load transfer from internally implanted devices to their surrounding bone tissues has been of great importance and interest. The frequent usage of metal for implanted materials creates a large stiffness difference between prosthesis and bone tissue, known as the stress shielding effect, and often leads to failure of the implant due to the large stresses created at the interface [83]. Methods of design to overcome the consequences of this effect were developed, such as a design with porous structure to provide a gradient modulus distribution for the purposes of minimizing the stress shielding effect and extending the lifespan of the implant [84].

Implant design has also included the formulation of the optimal contacting surfaces through which the load bearing is transmitted across the joint. An example is the knee joint, whereby a criterion of minimal slippage (or gliding) is utilized for achieving minimal shear stresses [85]. For the hip joint replacements, optimization techniques based on machine learning have been suggested [86]. Efforts were also aimed to optimize and individualize the positioning parameters of a femoral component in order to facilitate its accurate implantation [87].

6. The Contributions in This Special Issue

The current special issue includes six contributions [88–93], which cover a variety of topics ranging from modelling of load transfer in artificial joints and orthopaedic implants to recent advances in EMG analysis techniques, highlighting recent research and technology developments in the field of Orthopaedic and Rehabilitation Engineering. The first contribution [88] presents a finite element analysis of lumbar spine hybrid fixation vertebra-plasty combined with Cement-Augmented Screw Fixation. The study shows that the hybrid fixation method presented can lead to better stabilization of the spine and reduce the risk of implant failure, through slowing the progression of screw loosening by decreasing the range of motion. Whereas the findings appear tentatively promising, the model also contained some practical limitations and weaknesses that needed solving. For example, the model did
not include the mechanical effects of muscle contraction. Therefore, it was not possible to determine an accurate representation of true physiological loading conditions in the model.

The second contribution [89] deals with the implementation of a single actuated pneumatic artificial muscle (single-PAM) combined with a torsion spring for a one degree-of-freedom (1-DOF) robotic lower-limb wearable accessory. The authors demonstrated that using a fuzzy sliding mode controller (FSMC) to control the path tracking could control the tracking angle error within 0.5 degrees. The system showed better robustness against changes in the external environment as compared to the proportional integral derivative (PID) controller, which had a larger overshoot and slower response. Based on this finding, it was concluded that single-PAM with a torsion spring can be considered as an alternative actuating system for a robotic lower-limb system in rehabilitation settings. The authors proposed that this novel design would reduce the size, complexity and production cost of the wearable accessory and improve its portability and convenience as compared to the more frequently used wearable accessories driven by dual-actuated pneumatic artificial muscles (dual-PAMs).

The third contribution [90] deals with the evaluation of the wear-simulation response of custom-fabricated parts for artificial temporo-mandibular-joint (TMJ), including the electron beam melted titanium (EBM-Ti), zirconia and acrylic. The findings from this study demonstrated that the use of custom fabricated zirconia condyle and glenoid fossa resulted in greater wear (in terms of mean reduction in weight of the prosthetic TMJ parts) on the other biomaterials. Specifically, acrylic and EBM-Ti condyle and fossa parts exhibited greater wear in comparison to the zirconia fossa or condyle parts against which they were tested. Based on the findings, it was concluded that custom fabrication of alloplastic TMJ condyle and glenoid fossa parts can make a viable alternative to stock and custom fitted TMJ replacements. Furthermore, the authors proposed that EBM-Ti and acrylic had good biomechanical stability during simulation testing and that accurate custom-fabrication of the TMJ parts is possible. The use of zirconia as a biomaterial for customized alloplastic TMJ replacement requires further examination.

The fourth paper [91] evaluated the diagnostic accuracy of physical examination and magnetic resonance imaging (MRI) in knee injuries. The study included 96 participants, of whom 32 were diagnosed with total anterior cruciate ligament (ACL) ruptures, 45 with medial meniscus lesions, and 17 with lateral meniscus lesions. Physical examination and MRI scans were compared with knee arthroscopy findings as a golden standard for meniscal and ligamentous lesions. Analyses show that: (1) As compared to physical examination, MRI is more accurate in diagnosing medial and lateral meniscus lesions but the difference in diagnostic accuracy between the two methods is not statistically significant and (2) MRI shows a statistically significant lower accuracy in detecting ACL deficiency than physical examination. Based on these findings, the author proposed that physical examinations are grossly superior to the MRI in detecting ACL deficiency, and that MRI has limited application in detecting isolated ACL tears. They further suggested that physical examination of the knee joints should be implemented in a daily routine and that patients should be referred to MRI to answer specific questions about the morphology of lesions prior to surgery, rather than to confirm diagnosis.

The two last contributions are review articles related to recent advances in EMG analysis techniques [92] and the combined use of EMG and near-infrared spectroscopy (NIRS) methods in order to assess muscle characteristics from the electrical and hemodynamic points of view [93]. The review paper of Toledo-Pérez et al. [92] provides an overview on methodological approaches related to classification and processing of EMG signals. The authors focused specifically on the Support Vector Machines (SVM) technique, the primary function of which is to identify an n-dimensional hyperplane to separate a set of input feature points of the EMG signal into different classes using time-domain and/or spectral-domain features of the signal. The review examines the techniques used to make the classification in each reference. Its report includes the obtained accuracy, the number of signals or channels used, the way the authors made the feature vector, and the type of kernels used. The authors concluded that: (i) The most common kernel used is radial basis function (RBF), followed by linear function and Gaussian; (ii) principal component analysis (PCA) is the most common tool for
dimensionality reduction; (iii) mean absolute value (MAV), slope sign changes, zero crossings (ZC) and waveform length (WM) of the EMG signal are the most utilized time-domain features and (iv) many channels are not necessary to obtain good precision.

Finally, Scano et al. [93] provided a systematic review of the literature reporting the use of simultaneous measurement of surface EMG and NIRS for clinical applications. The eligible studies for inclusion in the review were studies where both techniques were combined in order to assess muscle characteristics from the electrical and hemodynamic points of view. The authors justified the use of the two methods in clinical practice, arguing that the EMG can give information about the muscular fibres, whether they are recruited in a higher number or in a different way during the rehabilitation process, while NIRS can contribute to the characterization of the muscle from a metabolic point of view. The authors discovered that the combined use of EMG and NIRS has been only partially exploited in clinical practice for the assessment and evaluation of patients with muscular dysfunction. However, they proposed that the field shows promise for future developments. The authors also put forward some of the challenges ahead, suggesting that: (i) NIRS is a relatively recent technique, and is difficult to find in the clinic, both NIRS and EMG instruments and that (ii) interpretation of data coming from both techniques requires the employment of technical staff, which is often not available in the clinical environment.

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