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Multi-muscle activation strategies during walking in female post-operative total joint replacement patients

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A B S T R A C T

Dynamic knee joint function requires coordinated multi-muscle activation patterns (MMP) that may be adversely affected by total knee arthroplasty (TKA). This study identified MMP changes in post-operative female TKA patients using a Support Vector Machine (SVM). It was hypothesised that TKA patients can successfully be classified and display significant alterations in temporal and spectral muscle activation characteristics. 19 female subjects (10 unilateral gender-specific TKA, 62.2 ± 8.6 yrs, BMI 28.2 ± 5.4; and 9 healthy controls, 61.4 ± 7.4 yrs, BMI 25.6 ± 2.4) were recruited. Surface electromyograms (EMG) were obtained for 7 lower limb muscles during walking. Stance phase (±30%) EMG data were processed using a wavelet transform and normalized to total power. Data across all muscles were combined to form MMPs and analyzed using a SVM. Recognition rates for all subjects were computed for MMPs and individual muscles. A binomial test was used to establish statistical significance ($p < 0.05$). The results supported the hypothesis indicating significantly altered muscle activations for vastus medialis (recognition rate ~68.4%) and biceps femoris (recognition rate ~73.7%). Further analysis identified distinct between group differences across temporal, spectral and intensity domains. Application of a combined SVM and MMP approach may be beneficial for the future assessment of post-surgical dynamic muscle function.

1. Introduction

Total knee arthroplasty (TKA) is one of the most common orthopaedic surgical interventions used to treat patients with extreme pain and limited function of the knee joint. Over the past 7 years TKA numbers increased by ~65% in Canada, with the leading cause for replacement being degenerative osteoarthritis (OA) (95%) (CIHI, 2014). Increased use and a more active aging population raise expectations for performance in more demanding and recreational activities after TKA (Nilsdotter et al., 2009).

Despite being a highly successful procedure for mediating pain, TKA patients often experience functional impairment or abnormal movement, loading and/or muscle activation patterns compared to healthy peers (Su et al., 1998; Benedetti et al., 2003; Catani et al., 2003; Mizner and Snyder-Mackler, 2005; Noble et al., 2005; Berti et al., 2006; McClelland et al., 2011). Walking is a complex task requiring coordinated activation of multiple agonistic and antagonistic muscles to enable stable walking at different speeds and surfaces (Winter, 2009). Alteration of these multi-muscle patterns (MMP), in response to musculoskeletal diseases such as OA and/or surgical interventions such as TKA, may in turn lead to abnormal gait patterns including "stiff knee" (Dorr et al., 1988) or "quadriceps avoidance" gait (Berchuck et al., 1990).

Electromyography (EMG) has revealed changes in the temporal and spectral activation characteristics within and across lower limb muscles in OA and following TKA. Co-activation patterns may be observed across muscles of the lower limbs and have been associated with attempts to improve dynamic joint stability (Noyes et al., 1992), control post-operative movement kinematics (Banks et al., 2003), and compensate for reduced muscle strength and size (Huang et al., 1996; Lewek et al., 2004b; Mizner and Snyder-Mackler, 2005; Stevens-Lapsley et al., 2010). Joint pathologies may also be reflected by changes in signal amplitude and contraction frequency. Reduced signal amplitude and frequency may be observed in muscle atrophy as a result of decreased motor unit recruitment or changes in muscle fiber type distribution (Solomonow et al., 1990; Wakeling and Syme, 2002; Wakeling et al., 2002). Historically, changes in the EMG have been treated either in the time or frequency domains in isolation. However,

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given the apparent complexity of change of MMP characteristics, quantification of change may benefit from the application of analysis strategies to simultaneously provide clinically relevant information on temporal and spectral changes.

Wavelet based time/frequency analysis has been successfully applied to EMG data (von Tscharner, 2000) revealing spectral, timing and intensity differences of muscular activations in patients with ankle OA (von Tscharner and Valderrabano, 2010; Nüesch et al., 2012). Combining wavelet patterns for multiple muscles to form a MMP further allows for the simultaneous investigation of inter- and intra-muscle activations and their corresponding spectral properties (von Tscharner and Goepfert, 2003; von Tscharner and Valderrabano, 2010). A promising approach for the analysis of changes in such MMPs is the use of support vector machines (SVM). This vector-based data classification method (Schölkopf and Smola, 2002; Shawe-Taylor and Cristianini, 2004) uses a supervised learning model to classify data based on an associated learning algorithm. SVMs have been successfully implemented for movement mechanics and EMG data to classify based on age (Begg and Kamruzzaman, 2003; Eskofier et al., 2013), injury (Lai et al., 2009) and pathology (Güler and Koçer, 2005). However, there remains a lack of information on the ability to utilize lower limb MMPs to classify healthy and post-surgical TKA populations and the contributions of individual muscles to such classification. Further, new approaches are needed to aid in assessing temporal and spectral changes within and across muscles forming the MMP.

The objective of this study was to assess differences in muscle activation strategies across superficial muscles of the lower limb in a cohort of post-operative female TKA patients compared to age matched healthy female controls. The hypothesis was that TKA patients can successfully be classified based on differences in lower limb muscle activation patterns during walking. Muscle activity patterns were explored to identify temporal and spectral differences between groups that may contribute to successful pattern recognition. Further, EMG and gait parameters were explored to identify potential contributions to neuromuscular adaptations.

2. Methods

2.1. Subjects and criteria

Ten post-surgical (19 ± 3 months) female subjects (TKA group; 61.9 ± 8.8 years; BMI 28.0 ± 5.3) with a primary, unilateral TKA (Gender Solutions NexGen High-Flex Knee; Zimmer Inc., USA) and nine healthy age-matched female controls (CON group; 61.4 ± 7.4 years; BMI 25.6 ± 2.4) volunteered for this study. Participants were excluded if they had functional impairments rendering them unable to perform activities of daily living or had medical conditions and/or recent surgery affecting mobility. CON subjects were excluded if they had ever undergone surgery on the lower limbs, experienced consistent joint pain, or had conditions that adversely affect mobility. Ethical approval was obtained from the local ethics board and informed consent was obtained from each subject before testing.

2.2. Study protocol

Subjects walked at a self-selected pace in the laboratory using a raised wooden walkway (10.97 × 1.83 m) with two forceplates (AMTI, OR6-6, USA and Kistler Instrumente, 9286AA, Switzerland) integrated centrally in the walkway. Subjects performed a task familiarization to identify the subject-specific preferred pace. Gait velocity was recorded using a pair of timing lights (Banner Engineering Corporate, Multi-Beam, USA) positioned immediately before and after the forceplates (2.35 m spacing). Following recommendations by SENIAM (www.seniam.org) EMGs of 7 lower limb muscles of the affected limb (TKA) and a randomly assigned limb (CON) were recorded. Small patches of skin were shaved and cleaned with rubbing alcohol and bipolar Ag/AgCl EMG electrodes (diameter 10 mm, interelectrode distance 20 mm; Noraxon, USA) were placed on the skin overlying the lower extremity musculature. Muscles of interest included vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), semitendinosus (SEM), biceps femoris (BF), lateral gastrocnemius (GAS) and tibialis anterior (TA). Subjects performed ten successful task repetitions consisting of contact of the limb in the center of one of the forceplates, a full complement of EMG data, and maintenance of gait velocity at ±5% of their mean self-selected pace. Ground reaction force (GRF) and EMG data were sampled at 1200 Hz throughout.

2.3. EMG analysis

2.3.1. Wavelet analysis

EMG data were time normalized prior to wavelet transformation in Matlab (The Math-Works, USA). A vertical GRF cutoff value of 2% peak force was used to identify stance phase for each limb. Stance phase was therefore defined as the period between heel strike (HS) and toe off (TO). To this period an additional 30% of stance phase was added to both sides to include muscle activity that occurred prior to HS and following TO. Thereafter the whole time period, 160% of stance phase, was subdivided in 501 points that were used to time normalize the wavelet transformed EMG intensities. As a result the matrices representing the EMG intensity had all the same size. Wavelet transformation was performed using ten non-linearly scaled wavelets (w) with center frequencies of 19–395 Hz (von Tscharner, 2000). Therefore, muscle activations were represented by the corresponding EMG intensity pattern with respect to time (abscissa) and the center frequencies of the wavelet filters (ordinate), where intensity represents the power of the transformed EMG signal (Fig. 1).

Signal noise, such as that resulting from motion artifacts, is an inherent concern in the collection of dynamic movement data. Such artifacts may be observed within specific frequency ranges (Conforto et al., 1999) covered by w_1 in the wavelet domain. To avoid pattern discrimination based on such noise all muscle patterns were visually inspected prior to inclusion in the analysis

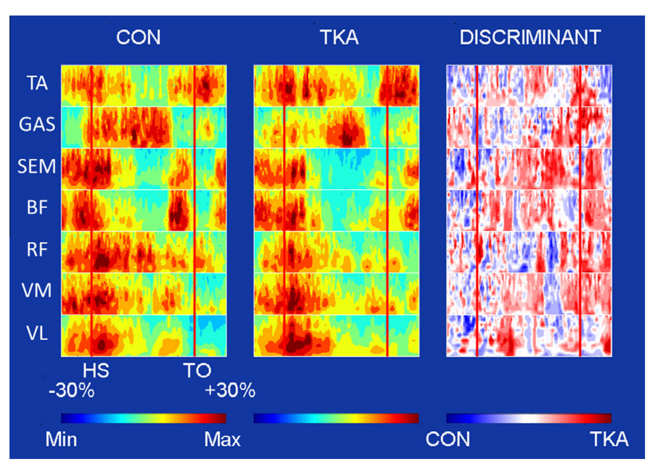

Fig. 1. Mean MMP and discriminant patters of CON and TKA groups during walking. All data were raised to the power of 0.1 to highlight areas of low intensity activity. Muscle patterns are displayed as contour plots with wavelets on the ordinate and time (normalized from HS to TO ± 30%) on the abscissa. Discriminant patterns display features unique to the CON group (blue) and TKA group (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)