THE CHARACTERIZATION OF PASSIVE ELASTIC JOINT MOMENT-ANGLE RELATIONSHIPS IN THE LOWER EXTREMITY

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INTRODUCTION
Passive elastic joint moments arise from the deformation of connective tissue surrounding a joint. Furthermore, motion at one joint may influence the passive elastic moment at a neighboring joint due to the stretch of bi-articular muscles (e.g. rectus femoris). Methods of describing bi-articulate coupling under active (Herzog, 1991) and passive (Edrich, 2000; Hoang, 2005; Riener, 1999; Vrahas, 1990) conditions have been investigated. However, prior approaches only consider a limited number of joint angle combinations, which limits the robustness of the approach. Furthermore, bi-articulate coupling facilitates the transfer of energy across joints. This coupling requires that passive joint moment-angle models be formulated that properly conserve energy. Finally, the identification of subject-specific moment-angle relationships is often not done, yet is relevant for understanding the role of passive forces during functional movement. The purpose of this study was to develop a comprehensive subject-specific method of describing the passive elastic joint moment-angle relationships about the hip, knee, and ankle while ensuring energy conservation across joints.

METHODS
Experimental procedure: Nine healthy young adults participated in the study. Subjects were positioned side-lying with their dominant limb supported on a table via low friction carts placed under the medial side of the thigh and leg. A padded brace prevented movement of the pelvis during testing. A physical therapist slowly manipulated the limb in 16 unique motion coupling trials of the hip, knee, and ankle using hand-held 3D load cells. Three-dimensional kinematics of the lower extremity and of the load cells were collected (100Hz) using a passive motion capture system (Figure 1). Load cell forces and moments were simultaneously recorded, and EMG signals from seven lower extremity muscles were monitored to ensure that the muscles remained relaxed.

Figure 1: The kinematics of reflective markers were monitored to characterize lower-extremity motion as well as the location of two hand-held load cells.

To evaluate the experimental method, eight additional validation trials were performed. Additionally, one trial was repeated three times within each test session (Figure 2).

Figure 2: Three trials of hip extension followed by knee flexion for the same subject. The graphs demonstrate the repeatability of the collected joint moment-angle measurements between trials.
Analyses: Three-dimensional joint moments were computed at the hip, knee, and ankle using the measured load cell forces, body segment kinematics, and joint center positions. A set of eight exponential functions that accounted for the stretch of uni-articular and bi-articular (rectus femoris, hamstrings, gastrocnemius) muscles were used to describe the relationship between the passive hip, knee, and ankle moments, and corresponding joint angles. Uni-articular exponential functions were described by two parameters (offset angle, stiffness). Bi-articular functions included a third parameter (the ratio of moment-arms between neighboring joints), thereby ensuring conservation of energy storage and release. A least squares approach was used to estimate the model parameters using subject-specific measurements. Validity of the parameters was evaluated by using the estimated parameters to calculate joint moments in the eight validation trials not used in parameter estimation.

RESULTS AND DISCUSSION
Similar trends in model parameter estimates were observed across subjects. Errors between measured and model-predicted joint moments were relatively small (Table 1). Similar results were obtained when applying the model to the unique data sets, thereby increasing confidence in the model validity. Inter-subject variability was apparent at all three joints suggesting subject-specific passive properties (Figure 3).

| Table 1: Mean (s.d.) root-mean-squared errors (in N-m) between model-predicted and measured joint moments. |
|-----------------|-----------------|-----------------|
| **RMS Errors**  | **Hip**         | **Knee**        | **Ankle**       |
| Identification trials | 3.1 (0.5)       | 1.4 (0.3)       | 0.7 (0.5)       |
| Validation trials   | 3.9 (2.5)       | 1.7 (0.7)       | 1.2 (0.5)       |

SUMMARY/CONCLUSIONS
It has been suggested that passive elastic mechanisms may serve as efficient energy storage and release mechanisms during normal gait (Ishikawa, 2005; Muraoka, 2005), and furthermore, that neuromuscular changes with age or injury may alter their usage (McGibbon, 2003; Edrich, 2000). The methods proposed here provide a consistent methodology to be used for quantifying the role of passive joint moments in abnormal gait or in muscle remodeling following surgery or athletic injury. Such analyses may provide new insights into the causes and compensatory mechanisms used to accommodate impairments.

REFERENCES

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