

CONTRIBUTIONS OF LEG MUSCLES TO THE AXIAL KNEE JOINT CONTACT FORCE DURING NORMAL WALKING

¹ Kotaro Sasaki and ² Richard R. Neptune

¹Department of Mechanical and Biomedical Engineering, Boise State University, Boise ID USA

²Department of Mechanical Engineering, University of Texas at Austin, Austin, TX USA
email: kosasaki@boisestate.edu

INTRODUCTION

Joint contact forces developed during dynamic motor activities can be significantly influenced by muscle forces [1, 2]. However, individual muscle force contributions to joint contact forces are not fully understood. Previous studies using inverse dynamics-based analyses have estimated joint forces during walking, typically by computing the sum of the contributions from the intersegmental joint forces and muscle forces that cross the joints of interest [3]. However, muscles can contribute to forces in joints that they do not cross through dynamic coupling [4], and therefore these approaches may neglect important contributions from specific muscles.

In contrast, muscle-actuated forward dynamics simulations are governed by the dynamic equations of motion, and therefore have the ability to quantify the contribution of every muscle to every joint force (e.g., [5]). The specific objective of this study was to use a muscle-driven forward dynamic simulation to identify individual muscle contributions to the knee joint force during normal walking, which has important implications for understanding the development and progression of osteoarthritis and other joint disorders in the knee.

METHODS

Muscle-driven forward simulation of walking

A sagittal-plane forward dynamics simulation of walking was generated using a musculoskeletal model (SIMM: MusculoGraphics) and deriving the equations of motion using SD/FAST (PTC). The model consisted of a trunk and two legs with 13 degrees-of-freedom and 25 Hill-type musculotendon actuators per leg (combined into nine functional groups). The tibiofemoral joint was modeled as a planar joint, with the position and orientation of the tibia being prescribed as functions of knee flexion angle [6]. Visco-elastic elements were attached to each foot

segment to model foot-ground contact [7]. Dynamic optimization was performed to fine-tune the muscle excitation patterns such that the simulation reproduced experimental kinematics and ground reaction forces (GRFs) over a full gait cycle (i.e., heel-strike to the subsequent ipsilateral heel-strike) [5]. Constraints on muscle excitation timing were imposed in the optimization to be consistent with experimental electromyography (EMG) to assure that muscles were generating force at the appropriate time in the gait cycle.

Experimental data

Previously collected experimental data (kinematics, GRFs and EMG) during walking at 1.2 m/s on an instrumented treadmill were used (n=10, age 29.6±6.1 years old, [8]). Kinematics, GRFs and surface EMG from 7 muscles were collected at 120, 480 and 1200 Hz, respectively, for 15 seconds. Low-pass filtered kinematic and GRF data (6 and 20 Hz cut-off frequencies, respectively) and EMG linear envelope were time-normalized to the gait cycle, averaged within and then across the subjects to obtain a group average.

Muscle contributions to knee joint force

The axial knee joint force (the force component parallel to the longitudinal axis of the tibia) over the gait cycle was determined from the system equations of motion using SD/FAST. Individual muscle contributions to the axial knee joint force were obtained using a joint force decomposition technique [4].

RESULTS AND DISCUSSION

The maximum axial knee joint force was ~3 times body weight (one BW is equivalent to 736 N), which occurred during weight acceptance in early stance phase (Fig. 1: ~15% gait cycle). The magnitude was comparable to previous *in vivo* knee joint force measurements of ~2.8 BW [9]. The

quadriceps (rectus femoris and vastus muscles), hamstrings and gluteus maximus contributed substantially to the peak knee joint force during weight acceptance (Fig. 2: 0-20% gait cycle). The plantar flexors (soleus and gastrocnemius) also contributed to the knee joint force from mid- to late stance, with the gastrocnemius being the primary contributor (Fig. 2: ~20-55% gait cycle). The pronounced quadriceps and gastrocnemius contributions in this study are consistent with previous simulation work [10].

The simulation results highlighted that in addition to the major muscles crossing the knee joint (i.e., the quadriceps, hamstrings and gastrocnemius), muscles that do not cross the knee joint (e.g., soleus, gluteus maximus) can potentially be significant contributors to the knee joint force. These muscles are also among the primary contributors to ground reaction forces in walking [5], and thereby, contribute to knee joint force via dynamic coupling.

The results of simulation studies such as these have the potential to provide much insight into specific characteristics of pathological gait affected by joint diseases, such as knee osteoarthritis. For example, reduced knee extensor moment in early stance and reduced plantar flexor moment in late stance are often observed in knee osteoarthritis patients [11, 12], and may be related to the patients' desire to reduce their knee joint forces during walking. However, a challenging aspect of modeling-based joint loading studies is validation of the results as joint loading is difficult to measure *in vivo* during dynamic tasks such as walking. However, instrumented implants have provided important validation data [9, 13], and combining such data with detailed models is a promising area for future work.

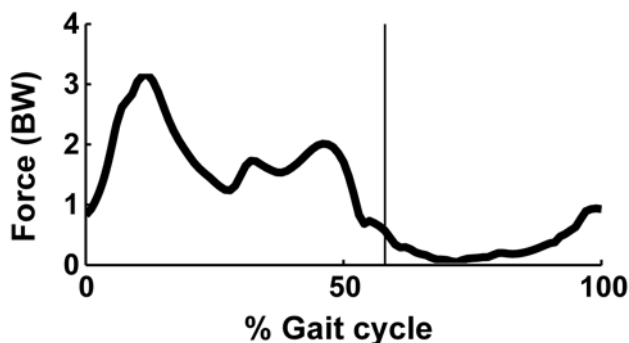


Figure 1: The axial knee joint force over the gait cycle. The vertical line represents toe-off.

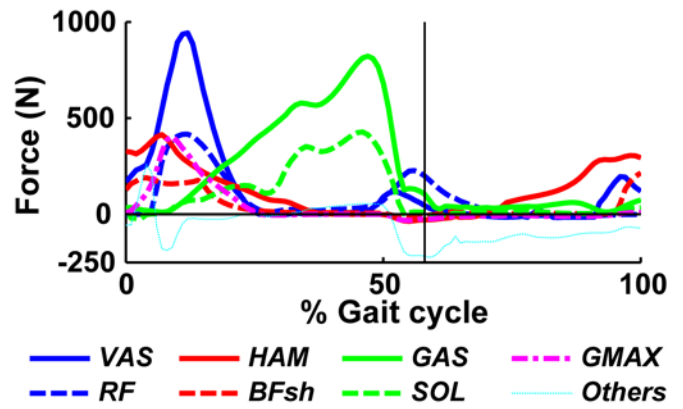


Figure 2: Individual muscle contributions to the axial knee joint force over the gait cycle. The vertical line represents toe-off. **VAS:** vastus muscles, **RF:** rectus femoris, **HAM:** hamstrings, **BFsh:** biceps femoris short head, **GAS:** gastrocnemius, **SOL:** soleus, **GMAX:** gluteus maximus, **Others:** all other muscles combined.

REFERENCES

1. Lu TW, et al. *J Biomech* **30**, 1101-1106, 1997.
2. Glitsch U and Baumann W. *J Biomech* **30**, 1123-1131, 1997.
3. Hardt DE. *J Biomech Eng* **100**, 72-78, 1978.
4. Zajac FE, et al. *Gait Posture* **17**, 1-17, 2003.
5. Neptune RR, et al. *Gait Posture* **19**, 194-205, 2004.
6. Yamaguchi GT and Zajac FE. *J Biomech* **22**, 1-10, 1989.
7. Neptune RR, et al. *Comp Meth Biomech Biomed Eng* **3**, 321-334, 2000.
8. Neptune RR and Sasaki K. *J Exp Biol* **208**, 799-808, 2005.
9. Heinlein B, et al. *Clin Biomech* **24**, 315-326, 2009.
10. Shelburne KB, et al. *J Orthop Res* **24**, 1983-1990, 2006.
11. Kaufman KR, et al. *J Biomech* **34**, 907-915, 2001.
12. Astephen JL, et al. *J Biomech* **41**, 868-876, 2008.
13. D'Lima DD, et al. *J Biomech* **40** (Suppl 1), S11-S17, 2007.