# Gastrocnemius Contraction Substantially Increases ACL Force in Knee Joint in Gait and in all Flexion Angles

Malek Adouni, A Shirazi-Adl, PhD, Hafedh Marouane.
Ecole Polytechnique, Montreal, QC, Canada.

**Disclosures:**
**M. Adouni:** None. **A. Shirazi-Adl:** None. **H. Marouane:** None.

**Introduction:** Gastrocnemius along with hamstrings and quadriceps are major lower extremity muscles that cross the human knee joint and in tandem with the knee passive articular-ligamentous structures resist the net external moments, control the movements and stabilize the joint under various daily and recreational activities. These functions become even more critical in the presence of joint injuries for example anterior cruciate ligament (ACL) ruptures and/or meniscal tears. Earlier studies have shown that quadriceps and hamstrings contractions act distinctly in respectively increasing or diminishing ACL force [1] while the effect of activity in gastrocnemius remains less clear [2, 3]. Adequate understanding of the role of these muscles, single or combined, is crucial in proper prevention and management of ACL ruptures and joint disorders. The current study was set to investigate biomechanics of the knee joint and forces in ACL under different gastrocnemius muscle activity levels. We used two different models; initially a musculoskeletal model of the entire lower extremity containing a detailed finite element (FE) model of the knee joint [4]was iteratively analyzed to compute muscle forces and knee joint stresses/strains at 75% stance phase of gait when the gastrocnemius force (LG+MG fascicles) peaks. These FE analyses were driven by reported kinematics and kinetics data collected during gait of asymptomatic subjects [5,6]. To analyze the sensitivity of the joint response and ACL force to changes in gastrocnemius activity level in gait, the geometrical properties of soleus muscle crossing the ankle joint were subsequently altered and analyses at 75% period of stance were repeated. To gain further insight, the response of the unconstrained knee joint alone was then analyzed in flexion ($0^o$ to $90^o$) under isolated gastrocnemius forces up to 1000 N. The effects of constraint on coupled rotations and changes in femoral footprint coordinates of muscle fascicles (LG and MG) were also investigated. It was hypothesized that gastrocnemius acts as an antagonist of ACL.

**Methods:** The musculoskeletal FE model considered bony structures (tibia, patella and femur), tibiofemoral (TF) and patellofemoral (PF) joints, major TF (ACL, PCL, LCL, MCL) and PF (MPFL, LPFL) ligaments, patellar tendon (PT), as well as hip and ankle joints plus detailed musculature of the lower extremity [4]. Nonlinear depth-dependent fibril-reinforced cartilage and menisci as well as ligaments with distinct nonlinear properties and initial strains were represented in the knee joint. This model incorporated the hip as 3D and the ankle as 1D spherical joint. The hip/knee/ankle joint rotations/moments and ground reaction forces at 75% of stance period corresponding to peak gastrocnemius contraction level were based on reported *in vivo* measurements [5,6] and were exploited to drive the model and evaluate muscle forces at the hip, knee and ankle using optimization (sum of cubed stresses). The knee joint nonlinear response was analyzed with updated (uni- and bi-articular) muscle forces as external loads along ground reaction forces and iterations at deformed configurations continued till convergence. To assess the sensitivity of results to changes in gastrocnemius activation, the gait analysis was repeated while altering the lever arm and area of the soleus muscle at the ankle joint in order to increase or decrease gastrocnemius activation level; (1) Min-G by assigning identical lever arms to both muscles (soleus and gastrocnemius) and increasing the soleus area by 20% whereas (2) Max-G by reducing (-20%) the reference lever arm and area of soleus [7]. In the second phase of this work, the knee joint alone was subject at different flexion angles (0°-90°) to isolated activation in gastrocnemius (LG+MG) up to 1000 N. Additional cases were studied at $0^o$ and $90^o$ joint flexion angles with the joint fixed in varus/valgus (V/V) and/or internal/external (I/E) rotations. To assess the effect of changes in the coordinates of LG-MG femoral footprints, the femoral insertions of both fascicles were also shifted at $0^o$ joint flexion by ±4 mm in A-P and M-L directions.

**Results:** In the lower extremity model during gait at 75% of stance, the LG/MG fascicle forces markedly altered from the initial reference values of 180N/508N [4] to either 119N/320N (Min-G) or 235N/627N (Max-G) (Fig. 1b). With the decrease in the gastrocnemius force (Min-G), hamstrings forces substantially increased but the quadriceps forces, albeit small, decreased (Figs. 1a,c,d). Reverse trends were computed when LG/MG forces increased (Max-G). The TF contact forces/areas/pressures were only slightly altered (Figs. 2b-d). Forces in ACL however significantly changed following the same trends in applied gastrocnemius (MG-LG) forces (Fig. 2a) while forces in other ligaments remained nearly the same. Antagonist effect of gastrocnemius contraction on ACL loading was further confirmed at all flexion angles by additional analyses of the knee joint under isolated activation of gastrocnemius (Fig. 3). Constraints on joint rotations decreased ACL load at both $0^o$ and $90^o$ flexion except for the fixed I/E rotation at $90^o$ flexion. Due to associated changes in anterior tibial translation, lateral or posterior shift in LG-MG femoral insertions slightly decreased ACL force whereas medial or anterior shifts slightly increased it.

**Discussion:** This work was performed to delineate the effect of different gastrocnemius activation levels on the knee joint biomechanics in general and ACL forces in particular. In the lower extremity model in gait at 75% stance period, changes in gastrocnemius activity primarily alter forces in hamstrings with little effects on quadriceps. Gastrocnemius muscle fascicles act as an antagonist of ACL in gait at 75% of stance phase when it is most activated. This antagonistic role of gastrocnemius is further demonstrated in the knee model under isolated activation of gastrocnemius at all flexion angles (Fig. 3). At smaller flexion angles (<$40^{o}$), the posterolateral bundle (ACL-pl) carries the entire force; 133 N at full extension under 1000 N muscle force. At larger flexion angles, the ACL-pl force however drops while the ACL-am share grows to its maximum of 157 N (90% of total ACL force) at $90^{o}$. These changes, in agreement with the literature [2], are associated with increases in the anterior tibia translation at all flexion angles. The knee joint flexion moment reaches its maximum of 31.2 Nm at $40^{o}$ flexion and minimum of 23.2 Nm at $90^{o}$ under 1000 N isolated gastrocnemius force that likely (when neglecting the joint passive contribution) depicts the lower efficiency (or smaller lever-arm) of gastrocnemius muscle at larger joint flexion angles.

**Significance:** While hamstrings and gastrocnemius are both knee joint flexors, they play quite opposite roles in respectively protecting and loading ACL. Although quadriceps muscles are also recognized as antagonist of ACL, this effect in contrast to the gastrocnemius is evident only at near full extension [1] and diminishes thereafter at larger flexion. The fact that gastrocnemius is clearly an antagonist of ACL at all flexion angles, especially at near full extension and larger flexion, should be exploited in effective prevention of ACL injuries, in coping with an ACL injury and in rehabilitation periods after an ACL reconstruction regardless of gender.

**Acknowledgments:**

Supported by the Natural Sciences and Engineering Research Council of Canada.

**References:** [1] Mesfar & Shirazi-Adl, CB 21:841, 2006 [2] Fleming et al, JOR 19:1178, 2001 [3] Durselen et al, AJSM 23:129, 1995 [4] Adouni et al, JB 46:619, 2013 [5] Astephen et al, JOR 26:332, 2008 [6] Hunt et al, CB 16:592, 2001 [7] Delp et al, IEEE-BE, 54:1970, 2007.

***ORS 2014 Annual Meeting***

**Poster No: 1692**