# Does unloading muscles save you energy? - Paradoxical effects of spring-loaded ankle exoskeletons on plantar flexor muscle mechanics and energetics

**Introduction** Muscles with compliant tendons undergo stretch-shortening cycles during gait and are able to store and return energy in their tendons. This mechanism can reduce contractile element work and shortening velocities, serving to reduce metabolic energy consumption. Ankle plantar-flexors (PF) are exponents of this mechanism and utilise a tuned muscle-tendon interaction during healthy gait. Inspired by biological elastic mechanisms, some assistive ankle robots or "exoskeletons" use elastic storage and return of energy in springs acting in parallel with the PF. While such devices help unload biological tissues, they might perturb the naturally tuned muscle-tendon interaction of PF. Therefore we aimed to examine the effects of ankle exoskeletons on PF muscle mechanics and link these effects to trends in metabolic costs. We hypothesised that exoskeletons would reduce metabolic energy consumption by reducing PF loading but this reduction would be limited owing to exoskeletons perturbing tuned PF muscle-tendon mechanics.

**Methods** Seven male participants hopped bilaterally at 2.5 Hz with and without elastic ankle exoskeletons. 3D motion capture data were used to reconstruct a rigid body model of the right leg and pelvis and combined with ground reaction forces in an inverse dynamic analysis to obtain leg joint kinetics. Surface electromyograms (EMG) were recorded from medial gastrocnemius (MG), lateral gastrocnemius (LG), soleus (SO) and tibialis anterior (TA). Ultrasound imaging was used to measure the length of SO muscle fascicles during hopping. Whole-body net metabolic power was determined via indirect calorimetry. To more directly link individual muscle mechanics and energetics we used the experimental data to drive simulations of muscle-tendon dynamics and energetics. Using a musculoskeletal model developed in OpenSim software we predicted muscle-tendon dynamics for MG, LG, SO and TA with and without exoskeletons. These dynamics then served as inputs to a model of muscle energetics that calculated muscle metabolic energy consumption.

**Results & Discussion** Experimental results showed that exoskeletons effected a reduction in muscular contributions to ankle joint kinetics, reduced SO EMG and whole body net metabolic power. Paradoxically, exoskeletons did not reduce SO fascicle mechanical work owing to a trade-off between increased fascicle length change and decreased SO forces. The modeling results showed no significant reduction in PF energy consumption with exoskeletons despite reductions in PF muscle forces. The simulations showed exoskeletons to increase PF fiber velocities and shift PF operating lengths to shorter and less optimal lengths. This resulted in less-favourable conditions for muscle force production and explained the lack of reduction in PF energy consumption with exoskeletons.