ISB 2013
BRAZIL
XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

# POWERED BIARTICULAR EXOSKELETON WITH GASTROCNEMIUS MIMICKING CONFIGURATION PRODUCES HIGHER REDUCTION IN METABOLIC COST THAN SOLEUS MIMICKING CONFIGURATION

Philippe Malcolm, Samuel Galle, Wim Derave, Dirk De Clercq
Ghent University, Department of Movement and Sports Sciences
e-mail: philippe.malcolm@ugent.be

## SUMMARY
Different studies point to the efficiency of biological biarticular muscles however no exoskeleton has been built with a biologically inspired biarticular actuator configuration. We built a powered biarticular exoskeleton with an actuator configuration that mimics the eccentric-concentric behavior of the *m. gastrocnemius*. We found that this configuration produced a higher reduction than a condition that only mimics the concentric *m. gastrocnemius* behavior and a trend towards a higher reduction than a condition that mimics the *m. soleus* behavior. However, there was no reduction in metabolic cost versus walking without exoskeleton probably due to the high encumbrance of the biarticular exoskeleton.

## INTRODUCTION
Different studies mention the efficiency of biarticular muscles for human movement [1]. Consequently, it is often suggested that powered exoskeletons could become more efficient by means of actuators that transfer power over multiple joints [2]. A simulation study from van den Bogert proposes a multi-articular elastic coupling between joints that is different from the biological configuration [3]. However, experimental tests with an exoskeleton that was constructed according to the design from van den Bogert could not reproduce the expected results from the simulation [4].
As far as we know no attempt has been made to construct an exoskeleton with biarticular actuators that mimic the biological configuration. One study uses a prosthesis with biarticular actuator s but no metabolic effects are reported [5]. Therefore our aim was to study the metabolic effects of an exoskeleton with a biologically inspired biarticular actuator configuration. We build an exoskeleton that mimics the *m. gastrocnemius* configuration by means of a pneumatic artificial muscle in series with an elastic artificial tendon running from the thigh segment to the foot segment. To understand the effects of the location of the origin and the elastic artificial tendon we compared with three other meaningful exoskeleton configurations.

## METHODS
We tested 9 subjects (7♂, 2♀, 71±2 kg, 177±1 cm, 23±1 yr (s.e.m.)) during walking at 1.25 m $s^{-1}$ on a treadmill. The subjects wore bilateral hinged knee-ankle-foot exoskeletons. The knee joint height could be adjusted to match the subjects' anthropometry. The pneumatic muscles were controlled with a footswitch control algorithm (Labview).
We tested 5 conditions (Figure 1A):
- A condition that mimics the eccentric and concentric behavior of the *m. gastrocnemius* (GAS_ECO). The actuator origin was located on the medial and lateral side of the thigh segment via a V-shaped elastic component and a parallel non-elastic component which served to limit the maximum elongation.
- A condition that only mimics the concentric behavior of the *m. gastrocnemius* (GAS_CON). This condition is entirely similar to GAS_ECO except that the V-shaped connection to the thigh segment only consisted of the non-elastic component.
- A condition that mimics the concentric behavior of the *m. soleus* (SOL_CON). The origin was placed on the shank. There was no condition with elastic component due to space restrictions. This condition is similar to the exoskeleton configuration used in previous studies from our lab[6] except for a longer moment arm at the ankle.
- An unpowered reference condition (UNP).
- A shod reference condition (SHD).

In the GAS configurations the origin was positioned such that in the neutral standing position the ratio between the moment arm at the knee is about half of the moment arm at the ankle as it is in the biological *m. gastrocnemius* [7]. In all three actuated conditions the pneumatic muscles and artificial tendons were mounted such that they where maximally elongated with knee extended and ankle in 15° dorsiflexion.
Before the metabolic tests the subjects were allowed at least a total 18min of habituation to the different exoskeleton conditions. As we did not know beforehand the optimal actuation onset for the GAS conditions the onset timings were determined based on subjects' perception via two graded protocols. In one of the graded protocols onset was gradually shifted from 23 to 53% of the stride until the subjects indicated that the onset went past the optimum. In the other protocol the onset was shifted from 53 to 23%. The mean value from the ascending and descending protocol would be used for metabolic testing (Figure 1C). Actuation offset was always programmed at 60%. The habituation and actual protocol were semi-randomized.

In the actual protocol subjects walked for four minutes in each condition. In the last two minutes we measured:
- Net $O_2$ consumption (Oxycon)
- Exoskeleton mechanics (loadcell, Richmond industries)
- EMG of ankle, knee and hip muscles (Zerowire)
- 2D kinematics (Basler)

Differences between conditions were analyzed with paired t-tests. As we considered this as an explorative analysis we did not apply any correction for multiple testing [8].

## RESULTS AND DISCUSSION

In SOL_CON subjects perceived the onset to be optimal at 43±0% (s.e.m.) (Figure 1C). This corresponds exactly with the condition that was found to be metabolically optimal in a previous study with similar configuration which confirms that subjects can perceive optimal onset with good accuracy [9]. The chosen onset timings in GAS_ECO and GAS_CON respectively were 39±3% (s.e.m.) and 41±0% (s.e.m.). As such it appears that the elastic component and the possibly stabilizing [10] knee flexion moment from the actuators in the GAS conditions allow an earlier optimal onset.

The actuation onset timings reported in the abstract are “programmed” onset values. In the near future we will determine the actual actuation onset from the load cell data and check if the perceived optimal onset of concentric actuation matches the prediction of a simulation study with an elastic exoskeleton [11].

The net $\dot{V}O_2$ values in GAS_ECO and SOL_CON where significantly lower than in UNP (respectively ~13 and 6% lower, p≤0.04) (Figure 1B). The highest $\dot{V}O_2$ was found in GAS_CON and the lowest $\dot{V}O_2$ was found in GAS_ECO. The $\dot{V}O_2$ in GAS_ECO was significantly lower than in GAS_CON (~7% lower, p=0.02) and there was a trend towards a significantly lower $\dot{V}O_2$ in GAS_ECO than in SOL_CON (~7% lower, p=0.057).

From these preliminary results we can conclude that the addition of a series elastic component improves the function of our biarticular exoskeleton. Different authors listed the benefits of pneumatic artificial muscles as being lightweight, strong, and allowing elastic behavior [12]. However, the way in which pneumatic muscles are mostly used (without series elastic component) apparently does not allow eccentric elongation [13]. When contraction starts during the stance phase the pneumatic muscles are at close to maximal length which is where they have the strongest contraction force which inevitably forces the ankle into concentric contraction. The addition of a series elastic component probably allows a more natural eccentric followed by concentric actuation.

Although there was a trend towards a lower $\dot{V}O_2$ in GAS_ECO than in SOL_CON none of the conditions showed a significant reduction versus SHD which is in contrast to a previous study with the uniarticular version of our exoskeleton. Possible reasons could be the longer moment arm at the ankle of the current exoskeleton and the additional encumbrance from the thigh segment of the exoskeleton.

By the time of the conference we will analyzed the EMG, and kinematics in order to better understand other underlying mechanisms of the metabolic effects.

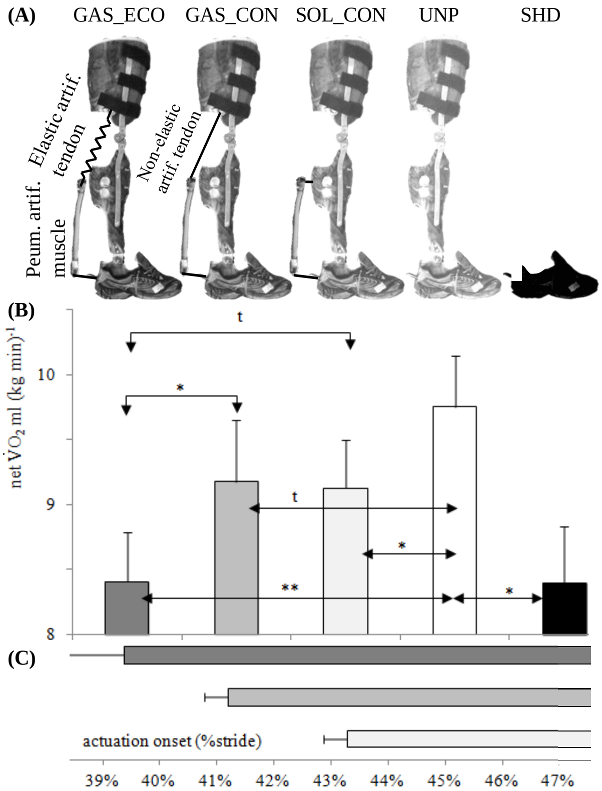


**Figure 1**: **(A)** Experimental conditions
**(B)** net $\dot{V}O_2$. T-bars represent s.e.m.
**=p<0.01, *=p<0.05, t=p<0.06
**(C)** Chosen actuation timings used in the different conditions (based on perception tests)

## CONCLUSIONS

The results show that it is possible to walk with a powered biarticular exoskeleton with m. *gastrocnemius* mimicking configurations. We found that this configuration works better with a series elastic component although the metabolic effect was smaller than with the uniarticular version of our exoskeleton probably due to the additional encumbrance from the thigh segment of the exoskeleton.

## ACKNOWLEDGEMENTS

The authors wish to thank Technische Orthopedie België and the department of Materials Science and Engineering for their help with constructing the exoskeleton, the M²Ocean labo for lending us the wireless EMG, Stijn Du Pré and Jonas Dupont for their help with the experiments and Maarten Afschrift for discussing the original concept.

## REFERENCES

1. van Ingen Schenau GJ et al., *J Anat*. **155**:1–5, 1987.
2. Ferris DP et al., *Int J H*. **4**:507-528, 2007.
3. van den Bogert AJ, *Biomed Eng Online*. **2**:17, 2003.
4. Van Dijk W et al. *ICORR*. 1–6, 2011.
5. Grimmer M, Seyfarth A, *Dynamic Walking*. 2009.
6. Malcolm et al. *PLOS ONE*, 2013.
7. Hof A, *J Biomech*. **34**:1085-1089, 2001.
8. Norris JA et al., *Gait Posture*. **25**: 620–627, 2007.
9. Malcolm, *PhD*. 2010.
10. Perry, *Gait Analysis*. 1992.
11. Bregman DJJ et al., *Clin Biomech*. **26**: 955–961, 2011.
12. Sawicki GS et al., *J Exp Biol*. **211**: 1402–1413, 2008.
13. Ferris DP et al., *J Appl Biom*. **21**: 189–197, 2005.