Functional Analysis of the Swing Leg Catapult in Human Walking

Alexandra Buchmann, Technical University of Munich, TUM School of Engineering and Design, Department of Mechanical Engineering, Chair of Applied Mechanics, 85748 Garching, Germany, alexandra.buchmann@tum.de

Bernadett Kiss, Dynamic Locomotion Group, Max Planck Institute for Intelligent Systems, 70569 Stuttgart, Germany, kiss@is.mpg.de

Daniel Renjewski, Technical University of Munich, TUM School of Engineering and Design, Department of Mechanical Engineering, Chair of Applied Mechanics, 85748 Garching, Germany, daniel.renjewski@tum.de

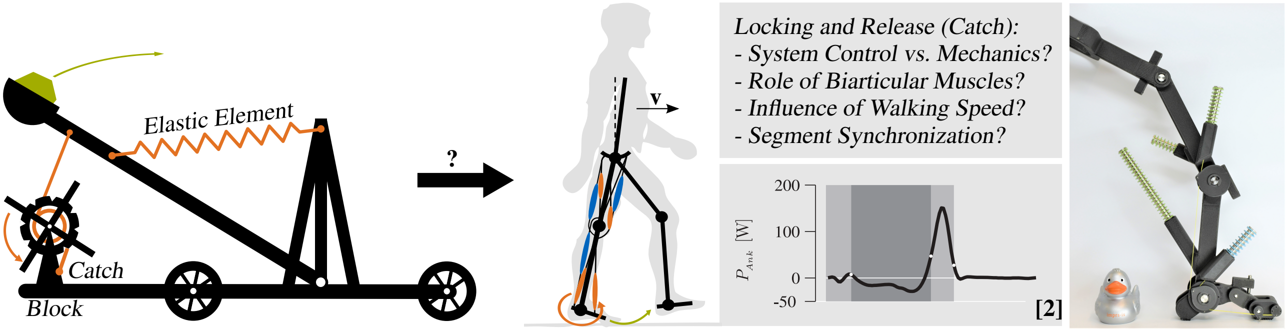
Alexander Badri-Spröwitz, Dynamic Locomotion Group, Max Planck Institute for Intelligent Systems, 70569 Stuttgart, Germany, sprowitz@is.mpg.de

Abstract

Keywords: push-off, energy storage, power amplification, catapult, locomotion, biomechanics

The *swing leg catapult* is a key mechanism for high efficiency in human walking and its functionality determines parts of the natural leg dynamics. In our new project *EcoWalk* we aim to identify the functional components of the catapult mechanism observed in the human leg focusing on the catch and release mechanism (CRM) using neuromuscular simulations in combination with a robotic model. The functional understanding of the mechanism will facilitate the improvement of gait rehabilitation devices and legged robots. We present a short literature review on catapult mechanisms in nature, explain the project design and show first simulation results.

A catapult mechanism is characterized by slow storage of elastic energy followed by a rapid energy release with substantially higher power accelerating a projectile. Three main components are present in a catapult: an elastic element, a block, and a catch with or without escapement (see figure 1).
In human walking an impulsive power output at the ankle joint is observed in late stance (see plot in figure 1). Hof et al. [1] were the first to propose that this ankle power burst during late stance of human gait is preceded by a slower energy storage phase. It has been shown that the catapult unloading indeed accelerates the leg into swing, thus the human leg is a catapult [2]. where the muscle-tendon-units (MTUs) of Soleus and Gastrocnemius, mostly operating isometrically during stance, facilitate elastic energy storage during stance and a rapid recoil at push-off [3, 4, 5].



Locking and Release (Catch):
- System Control vs. Mechanics?
- Role of Biarticular Muscles?
- Influence of Walking Speed?
- Segment Synchronization?

Figure 1 Schematic depiction of a catapult and its functional components on the left. The elastic element stores the energy to accelerate the payload. The block takes up the forces arising during slow loading. A ratchet mechanism (catch) locks the loaded catapult until it is fired. Slow loading during stance and rapid release of energy around push-off is also observed at the ankle joint in late stance of human walking (see ankle power curve from [2]). Our project aims to answer the central research questions around the CRM of the catapult in human walking given in the figure. A first leg-prototype of the robotic model is shown on the right.

Different types of catapult mechanisms were observed in animals such as horses [6], locusts, frogs, fleas or click beetles [7]. The CRM has been thoroughly studied and identified in these animals, in humans however the CRM has not been fully identified yet. The complex interplay between the thigh-shank-foot segment chain and MTUs makes the mechanism hard to understand. In addition, the catapult's existence in humans and its function, i.e., what happens to the released energy, is discussed controversially. Zelik, Huang, et al. [8] hypothesized that during leading leg touch-down, mechanical energy is dissipated in the foot-ground collision. By redirecting the center of mass (CoM), thus reducing the impact velocity of the leading leg, the trailing leg's push-off could reduce these collision losses. Lipfert et al. [2] in contrast argue, that in walking the knee buckles before push-off and a buckled knee would transfer only a small amount of its ankle push-off work into trunk motion. Instead, ankle push-off work mainly powers the leg swing. Although the theories seem contradictory [9] showed that both may apply as the swing leg motion also influences the CoM and vice versa.

To develop a functional understanding of the catapult, in particular the CRM (research questions see figure 1) we work with a two-pronged approach: evolving a NMS and building a robotic model. Hereinafter we focus on the NMS - the robotic part is only discussed shortly. We implemented a global optimization framework for an existing NMS from Geyer et al. [10] running on Matlab Simulink (MATLAB R2020b, MathWorks, Inc., Natick, MA, USA). Using the *genetic algorithm (Matlab GA)* and a custom cost function we optimized the model's 11 gains for four different walking speeds (0.5, 1, 1.3 and 1.6 m/s). The simulation results show good agreement with findings from Lipfert et al. [2]: the walking speed is proportional to ankle power output, thus the catapult gets stronger with increasing walking speed. The muscle activations increase with walking speed as expected. However the knee and ankle kinematics tend to become non-physiologically at faster walking speeds. Especially the stance knee flexion is missing in the optimized model. We therefore plan to change the foot-ground contact model including toes as suggested in [11] and will investigate the design of the cost function in more detail (compare e.g. [12]). With the improved framework we will investigate the models gait in absence of biarticular muscles (GAS, HAM) to determine their influence on the catapult and perform a detailed analysis on the velocity dependency of the catapult. To validate the NMS-findings and transfer the insights to technical real world systems we build a walking, child size robotic model in addition. The first prototype is a non actuated robotic leg to study the influence of tendon routing and tendon stiffness ratios on the catapult (see figure 1 right hand side).

Acknowledgment

The project is funded by the Deutsche Forschungsgemeinschaft (DFG) No. 3991/2.

Literature

[1] Hof, A. L., Geelen, B. A., and van den Berg, Jw. "Calf muscle moment, work and efficiency in level walking; Role of series elasticity". In: *Journal of Biomechanics* 16.7 (1983), pp. 523–537. ISSN: 00219290. DOI: `10.1016/0021-9290(83)90067-2`.

[2] Lipfert, Susanne W., Günther, Michael, Renjewski, Daniel, and Seyfarth, André. "Impulsive ankle push-off powers leg swing in human walking". In: *Journal of Experimental Biology* 217.8 (2014), pp. 1218–1228. ISSN: 1477-9145. DOI: `10.1242/jeb.097345`.

[3] Fukunaga, Tetsuo, Kubo, K., Kawakami, Yasuo, Fukashiro, S., Kanehisa, Hiroaki, and Maganaris, Constantinos N. "In vivo behaviour of human muscle tendon during walking". In: *Proceedings. Biological Sciences* 268.1464 (2001), pp. 229–233. ISSN: 0962-8452. DOI: `10.1098/rspb.2000.1361`.

[4] Ishikawa, Masaki, Komi, Paavo V., Grey, Michael J., Lepola, Vesa, and Bruggemann, Gert-Peter. "Muscle-tendon interaction and elastic energy usage in human walking". In: *Journal of Applied Physiology (Bethesda, Md. : 1985)* 99.2 (2005), pp. 603–608. ISSN: 8750-7587. DOI: `10.1152/japplphysiol.00189.2005`.

[5] Lichtwark, Glen A., Bougoulias, K., and Wilson, Alan M. "Muscle fascicle and series elastic element length changes along the length of the human gastrocnemius during walking and running". In: *Journal of Biomechanics* 40.1 (2007), pp. 157–164. ISSN: 00219290. DOI: `10.1016/j.jbiomech.2005.10.035`.

[6] Wilson, Alan M., Watson, Johanna C., and Lichtwark, Glen A. "A catapult action for rapid limb protraction". In: *Nature* 421.6918 (2003), pp. 35–36. ISSN: 1476-4687. DOI: `10.1038/421035a`.

[7] Alexander, McNeill R. and Bennet-Clark, H. C. "Storage of elastic strain energy in muscle and other tissues". In: *Nature* 265.5590 (1977), pp. 114–117. ISSN: 1476-4687. DOI: `10.1038/265114a0`.

[8] Zelik, Karl E., Huang, Tzu-Wei P., Adamczyk, Peter G., and Kuo, Arthur D. "The role of series ankle elasticity in bipedal walking". In: *Journal of Theoretical Biology* 346 (2014), pp. 75–85. ISSN: 0022-5193. DOI: `10.1016/j.jtbi.2013.12.014`.

[9] Zelik, Karl E. and Adamczyk, Peter G. "A unified perspective on ankle push-off in human walking". In: *Journal of Experimental Biology* 219.Pt 23 (2016), pp. 3676–3683. ISSN: 1477-9145. DOI: `10.1242/jeb.140376`.

[10] Geyer, Hartmut and Herr, Hugh. "A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering : a Publication of the IEEE Engineering in Medicine and Biology Society* 18.3 (2010), pp. 263–273. DOI: `10.1109/TNSRE.2010.2047592`.

[11] Falisse, Antoine, Afschrift, Maarten, and Groote, Friedl de. "Modeling toes contributes to realistic stance knee mechanics in three-dimensional predictive simulations of walking". In: *PLOS ONE* 17.1 (2022), e0256311. ISSN: 1932-6203. DOI: `10.1371/journal.pone.0256311`.

[12] Veerkamp, K., Waterval, N. F. J., Geijtenbeek, T., Carty, C. P., Lloyd, D. G., Harlaar, J., and van der Krogt, M. M. "Evaluating cost function criteria in predicting healthy gait". In: *Journal of Biomechanics* 123 (2021), p. 110530. ISSN: 00219290. DOI: `10.1016/j.jbiomech.2021.110530`.

In: Achte IFToMM D-A-CH Konferenz 2022

DOI: 10.17185/duepublico/75443
URN: urn:nbn:de:hbz:465-20220222-173245-7