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Dynamics of human and artificial legged locomotion – running towards model-based predictions

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1 BACKGROUND AND RESEARCH GOALS

The dynamics of human locomotion such as walking, running and hopping is under active research for several reasons. The understanding of the dynamics of pedal locomotion is utilized in medicine, sports science and in robotics. The phenomena related to legged locomotion are researched by using both mathematical models and laboratory experiments. Mathematical models, which integrate the biomechanical features of the body and the functions of the central nervous system, have advantages over laboratory experiment in the sense that 1) the parameter region can be completely discovered and extended; 2) we get rid of measurement errors, which would make complicated to discover the sensitivity for the change of parameters. For instance, when we are curious about the effect of the knee angle on the energetic cost of running, the problem is that the energy consumption of a human is extremely challenging to measure in the required accuracy, since the variation of the knee angle might cause the energetic cost variation of 1-2% only, which is the same magnitude as the measurement errors.

The predictive mathematical models are capable of generating the motion of the locomotor without the collection of any measurement data. The mathematical modeling of legged locomotion systems includes several challenges: geometric nonlinearity is typical; time delay is involved if the feedback of sensory information is considered; legged systems are typically piecewise smooth systems with discrete dynamic events (hybrid dynamical systems) due to the periodically changing limb-ground contact scenarios; high degree-of-freedom models necessitates multibody modeling concepts such as dependent/redundant coordinate sets and geometric constraints; computationally demanding nonlinear optimization algorithms have to be used to find the motion of the predictive models and to mimic the optimization process performed by the nervous system.

Our project goal is to contribute to the discovery of the motion optimization strategies of the human nervous system. We identified how the certain biomechanical parameters affect the energetic costs and impulsive loads during human-like legged locomotion. These are considered as optimization cost functions. To reach this goal we mostly relied on mathematical models which incorporate the mechanical properties of the human body and a controller which plays the role of the nervous system. Our experimental results also contribute to the understanding of the human motion planning and optimization process.

The human motion is similar to the operation of robots in the sense that data are collected about the state of the body and about the environment, then a decision is made on the control action, finally, the control signals are sent to the muscles or motors. This process results in the reflex delay. We contributed to the understanding of the human balancing process considering the reflex delay, which might be helpful in the development of balancing assistant devices. Related to the main research direction, we also found that some of the robotic motion planning algorithms are actually result in human-like motion. This clearly helps to understand the human optimization processes. The results can be used for human-like motion generation in robotics and in animations. It is also possible to identify motoric disorders which cause the deviation of the human motion from the normal.

2 RESEARCH RESULTS

2.1 Predictive models of locomotion and the related numerical algorithms

The complexity of dynamic models of legged locomotion has a large variety. The most intricate high degree-of-freedom (DoF) models are usually capable of measurement data analysis, such as inverse dynamic models of the human body. On the other hand, simple dynamic models are predictive. It means that they generate the motion (hopping, running, or walking) by utilizing the nonlinearities in the dynamic equations or by using a control model that imitates the central nervous systems of the human or animal. One of the simplest models of such kind is the spring-loaded inverted pendulum (SLIP). The SLIP model was analyzed in many aspects in the project. We have found that the literature lack of papers with comprehensive discussion of the stability properties of the SLIP model. The discovery of the dimensionless parameter-space, the parameter identification for humans and for certain animals was done. A Hungarian language journal paper [j-1] and the conference abstract [a-4] have been published and a conference proceedings paper [s-i] is accepted.

An important goal of the investigation of the SLIP model was to test our numerical algorithms, with which more intricate models can be analyzed. The Nelder-Mead simplex optimization method was successfully tested on the SLIP model [j-3, a-4], and it is ready to be applied for our 6DoF segmented model of running and hopping presented in [j-9, c-6]. The optimization goal is to find the parameter sets which results in the most energy efficient motion or lowest impulsive joint loads. The results related to the numerical analysis of the segmented model are partially ready and will be published in the journal paper [p-iii], which is under construction. The results provide information about the effect of biomechanical parameters on the performance of the locomotion (e.g., we can provide a model-based prediction related to the effect of the knee angle on the energetic costs and impulsive joint loads in the human body).

The concept of optimization of the human motion is tangibly illustrated in [a-7], where a simple hopping model was used. We proved that there is a tradeoff between muscle power and impulsive joint loads, of which the linear combination is considered as cost function. We proved that an optimal motion exists.

The generally applicable mathematical description of constrained piecewise smooth (such as hopping) systems was described in [j-10]. Constrained systems are typical in multibody dynamics: for high DoF intricate mechanical models, the most efficient modeling approach is to use higher number of general coordinates than the DoF and to introduce constraints that describe the relation of these redundant/dependent coordinates.

2.2 Motion control in underactuated systems

Human body is usually modeled by rigid segments that are connected to each-other via joints. Thus, multibody simulation techniques are important. Besides, the nervous system is considered as a crucial part of the model. The nervous system provides the feedback loop and the input signals. Typically, human motion is underactuated, especially, when the limbs do not touch the ground. Underactuation means that the number of independent control inputs is lower that the DoF of the system. I.e., some DoFs are not controlled directly, but they move freely. Our modeling approaches necessitate theoretical research related to the motion control of underactuated multibody systems. Our results, which are published in [j-7, c-2, a-5], prove the practical applicability of certain underactuated control algorithms based on experiments and/or numerical simulations.

The research of underactuated control methods included the concept of optimization in a finite range of time. Papers [j-1, j-7] proves the feasibility of a control idea which does not make decisions based on the current information but looks ahead in time, which is called receding horizon control in general. The mathematical background of the control concept is based on variational principles. The control concept is similar to the operation of the human central nervous system in the sense that humans also plan the motion not only for the upcoming time instance but plan the motion for a finite time range.

Some of the underactuated motion control algorithms were tested on robot prototypes of which the position measurement technique required further investigation. The results related to pose estimation are published in [j-3, c-7, c-9, a-3]. We found that the position measurement accuracy and precision of a swept laser-plane based system depends not only on the speed of the moving object but on the acceleration and jerk too. Besides robotics, the results are useful in biomechanical measurements.

2.3 Human and robotic motion planning

When a robot fulfills a task, each joint position is calculated, with which the end effector of the robot moves on its prescribed trajectory. This operation is called as inverse kinematics. Roughly the same process is going on when humans plan their motion; e.g., when we want to reach for an object by our hand, the motion of the shoulder, the elbow and the wrist is carefully designed. Additionally, certain feedback helps to keep the end-effector/hand on the desired trajectory. Prior to this project, we have found that some of the robotic inverse kinematics algorithms are very close to the unknown human motion planning process. The stability properties of the feedback parameters were assessed in the project. The stable parameter regions are published in [j-4, c-4].

2.4 Muscle models and their effect on the stability

Two phenomena help to control and stabilize the human motion. The information collected by the sensory organs is processed by the central nervous system and the proper signal is sent to the muscles. This generates a response, which is relatively slow comparing to the so-called preflexes, which are the immediate response of the human body strictly based on the mechanical properties of the muscles and tendons. These mechanical muscle properties are incorporated in several types of muscle models. The preflexes, which can be considered as muscle response, provides stable hopping motion is certain parameter ranges.

Based on an earlier study from the literature, we carried out the stability analysis of vertical hopping. The most tangible novelty in our approach is that we dropped the numerical optimization of the muscle activation function, and we provided an analytical approach. The analytical approach provides better understanding of the underlying dynamic processes [c-1, p-ii]. The effect of muscle model properties was studied in the SLIP model too, and the requirements of stable hopping were published in [a-1].

2.5 Reaction time in the human motion control

Time-delay makes the investigation of the human motion control challenging. Time delay is present, since the signals from the sensory organs travel to the central nervous system, then after the processing of the data the proper signals are sent to the muscles, which processes take a short but not always negligible reaction time. This delay depends on many factors, such as age, fatigue, practice and health. Time-delay highly affect the balancing abilities during both standing and locomotion. We successfully applied linear feedback controls as the model of the human balancing process. The related results are summarized in the papers [j-5, j-6].

The delay effect was investigated in case of the motion control of robots too. The stability properties of a fundamental model of underactuated systems will be published in [s-iii].

Delay effects in the balancing of objects are explained in [c-5]. An experimental device has been developed to assess the reaction time (also known as reflex delay) in a variety of sensory inputs and reaction movements [j-8]. For instance, the reaction time between a visual input and a finger button push can be measured. The reflex delay is different for a different pairing, e.g. for audial input with foot pedal push.

Time delay cause an oscillation of the human body about the equilibrium. This oscillation requires a certain amount of mechanical energy. The energetic costs of balancing during standing and hopping were compared in [c-8]. We have found that the energetic cost devoted to the motion stabilization can be lower during locomotion than in standing. This suggests that locomotion is an energy efficient way of preventing fall over.

2.6 Experimental results on the effect of acceleration and deceleration

One of the main goals of the project is to discover the motion planning and motion optimization strategy of the human locomotion. We suppose that there are certain cost functions behind the optimization process. Therefore, we focused on the exploration of the changes in human body kinematics and kinetics, related to well-defined cost functions, such as energy dissipation, energy conservation or energy accumulation. These cost functions are in analogy with deceleration, constant speed locomotion and acceleration. Hence, we collected measurement data with five different tasks: 1) slow, 2) convenient, 3) high speed running, 4) acceleration and 5) deceleration. The kinematic data were collected by a motion capture system, while the foot pressure data were collected by insole sensors. Correlation tests showed that the effect of varying speed and varying acceleration can be distinguished. Furthermore, we identified the biomechanical properties (e.g., knee angle, torso lean angle and ground reaction forces) which are related to the acceleration and the deceleration. Following the idea, that acceleration/deceleration are in correspondence with energy accumulation/absorption, we can consider these identified biomechanical properties as the ones which are tuned by the human nervous system to achieve better energy efficiency. Our experimental results are collected in the journal paper under resubmission [p-i] and in conference publications [c-3, a-2, a-6, s-ii].

2.7 Experimental results on the adaptation to ground elasticity

Acknowledging the idea that the human nervous system continuously collecting data from the environment and performing the corresponding optimization of the motion, we hypothesized that the human motion adapts to the change in the ground elasticity. We conducted an experiment, in which the athletes were running on asphalt and rubber surface. The experiment aimed to gain new information about the effect of the soil elasticity on the kinematic parameters of locomotion. In parallel, a mechanical model (extended SLIP model) has been set up for measurement result interpretation. The preliminary results show that certain biomechanical parameters shows significant difference in different ground elasticity. These results were presented in an MSc thesis and a journal/conference publication is planned after the project: [p-iv].

3 DISSEMINATION OF THE RESULTS AND EDUCATION

Related to the project, 9 journal papers were published [j1-j10], 9 conference papers [c1-c9] and 7 extended abstracts [a1-a7] have been published (14 conference talks total during the 46 months).

The PI of the project was the co-organizer of the Eccomas Multibody Conference 2021, Budapest (10th conference in the series ''ECCOMAS Thematic Conference on Multibody Dynamics''). A special session on legged locomotion was organized under the name ''Applied biomechanics and gait analysis''.

5 BSc and 2 MSc thesis and 2 TDK (Scientific Student Competition) studies were completed. Two PhD students worked on the project in full time: Dóra Patkó (research topic: muscle models in the nonlinear dynamic models of human walking, hopping and running) and Liliána Zajcsuk (research topic: Analysis of the human legged locomotion by multibody models supplemented with motion control). In part time, Bálint Bodor and Roland Zana are working on the project (research topic: motion control of underactuated systems, humans' reflex delay).

Some of the project outcomes (and publications) were achieved with international cooperation. Prof. Bernd Krauskopf (University of Auckland, New Zealand) and Prof. Petri Piiroinen (Chalmers University of Technology, Sweden) provided essential contribution in the theoretical work related to nonlinear dynamics and the numerical methods in piecewise smooth systems, which is acknowledged.

4 PLANNED PUBLICATIONS TO BE SUBMITTED/RESUBMITTED AFTER THE PROJECT

Some of the results of the project (achieved at the final period) will be possible to publish in the upcoming months. The list of the planned papers is below.

[p-i] Zajcsuk, L, Zelei, A: Biomechanical Performance Measures of Running During Deceleration and Acceleration. Rejected submission (Journal of Electromyography and Kinesiology). Expected resubmission: June 2024.
[p-ii] Patkó, D, Zelei, A: Muscle models integrated into low DoF self-sustained hopping models. Expected submission: March 2024.
[p-iii] Zelei, A, Bálint, G., Habib, G.,: Discovery of the relation between biomechanic parameters and cost functions in hopping by assessing gradients. Expected submission: December 2024.
[p-iv] Zajcsuk, L., Nagy, B., Zelei, A.: How do runners adapt to ground surface quality? The effect of ground elasticity on biomechanical factors. Expected submission: December 2024.

5 SUBMITTED PUBLICATIONS

Here we collect the journal and conference papers which are submitted and are under review.

[s-i] Nagy, Á. M., PAtkó, D., Zelei, A.: Discovery and Interactive Representation of the Dimensionless Parameter-Space of the Spring-Loaded Inverted Pendulum Model of Legged Locomotion Using Surface Interpolation. Springer Proceedings in Mathematics and Statistics. (Accepted, under publication)
[s-ii] Zajcsuk, L., Zelei, A.: Correlation of Biomechanical Performance Measures with Speed, Acceleration and Deceleration in Human Overground Running. Springer Proceedings in Mathematics and Statistics. (Accepted, under publication)
[s-iii] Zana, R. R., Zelei, A.: Discrete Time Stability of an Underactuated Inverse Dynamics Control based on the Augmented Lagrangian Formalism. Journal of Vibration and Control. Under review, 3rd round.

6 PUBLICATIONS

6.1 Journal papers

[j-1] Bodor, B., Bencsik, L.: Variational principles for the trajectory tracking control of underactuated mechanical systems. Journal of Computational and Nonlinear Dynamics, Joint Special Issue on Design and Control of Responsive Robots. 2023, 18(6): 061002.
[j-2] Patkó, D., Nagy, Á. M., Zelei, A.: A futás és szökdelés tömeg-rugó modell dinamikai viselkedésének globális feltérképezése és paraméterhangolása (Global analysis and parameter tuning of the dynamic behaviour of the slip model of running and hopping), Biomechanica Hungarica 15(1):39-50, 2022, doi: 10.17489/biohun/2022/1/308.
http://biomechanica.hu/index.php/biomech/article/viewFile/308/418
[j-3] Zana, R. R. and Zelei, A.: Feedback motion control of a spatial double pendulum manipulator relying on swept laser based pose estimation, International Journal of Optomechatronics 15(1):32-60, 2021, doi: 10.1080/15599612.2021.1890284.
https://www.tandfonline.com/doi/full/10.1080/15599612.2021.1890284
[j-4] Patkó, D. and Zelei, A.: Velocity and acceleration level inverse kinematic calculation alternatives for redundant manipulators, Meccanica 56:887-900, 2021, doi: 10.1007/s11012-020-01305-z.
https://link.springer.com/article/10.1007/s11012-020-01305-z
[j-5] Zelei, A., Milton, J., Stépán, G., Insperger, T.: Response to perturbation during quiet standing resembles delayed state feedback optimized for performance and robustness, Scientific Reports 11:11392, 2021, doi: 10.1038/s41598-021-90305-4.

https://www.nature.com/articles/s41598-021-90305-4
[j-6] Molnár, C. A., Zelei, A., Insperger, T.: Rolling balance board of adjustable geometry as a tool to assess balancing skill and to estimate reaction time delay, Journal of the Royal Society Interface 18(176):20200956, 2021, doi: 10.1098/rsif.2020.0956.
https://royalsocietypublishing.org/doi/10.1098/rsif.2020.0956
[j-7] Bodor, B., Zelei, A., Bencsik, L.: Predictive trajectory tracking algorithm of underactuated systems based on the calculus of variations, ASME Journal of Computational and Nonlinear Dynamics 16(8):081002, 2021, doi: 10.1115/1.4051168.
https://asmedigitalcollection.asme.org/computationalnonlinear/article-abstract/16/8/081002/1109301/Predictive-Trajectory-Tracking-Algorithm-of?redirectedFrom=fulltext
[j-8] Zana, R R, Zelei, A: Introduction of a Complex Reaction Time Tester Instrument. Periodica Polytechnica Mechanical Engineering 64(1):20-30, 2020, doi:10.3311/PPme.13807.
https://pp.bme.hu/me/article/view/13807/8567
[j-9] Zelei, A., Krauskopf, B., Piiroinen, P. T., Insperger, T.: Stable periodic motion of a controlled segmented leg model of pedal locomotion with inelastic ground-foot collision. Nonlinear Dynamics, 97(3):1945-1958, 2019. Doi:10.1007/s11071-019-04911-z.
https://link.springer.com/article/10.1007/s11071-019-04911-z
[j-10] Zana, R. R., Bodor, B., Bencsik, L., Zelei, A.: A Tutorial for the Analysis of the Piecewise-Smooth Dynamics of a Constrained Multibody Model of Vertical Hopping. Mathematical and Computational Applications, 23(4), 2018, doi:10.3390/mca23040074.
https://www.mm.bme.hu/~zelei/zelei_pub/zana_2018_MCA.pdf
https://www.mdpi.com/2297-8747/23/4/74

6.2 Conference papers

[c-1] Patkó, D., Zelei, A.: Symmetry, benefit or disadvantage? Energy consumption of simple hopping model with intrinsic muscle properties. The 6th International Conference on Dynamics, Vibration and Control, 21-24 Oct 2022, Shanghai. (Abstract accepted, 6 pages paper under review). (Submitted: July 30., 2022)
[c-2] Zana, R. R., Zelei, A.: Inverse Dynamics Control of a Crane-Like Underactuated Multibody System with Penalty Formulation. The 6th International Conference on Dynamics, Vibration and Control, 21-24 Oct 2022, Shanghai. (Abstract accepted, 6 pages paper under review). (Submitted: July 30, 2022)
[c-3] Liliána Zajcsuk, Zelei Ambrus: Emberi futás kinematikai és kinetikai paramétereinek kísérleti elemzése gyorsítás és lassítás esetén (Investigation of the kinematic and kinetic parameters of the human running in case of acceleration and deceleration based on measurements). XXVIII. Nemzetközi Gépészeti Konferencia - OGÉT, Nagyvárad, Romania (on-line conference), 2020. 25-26. April.
https://www.mm.bme.hu/~zelei/zelei_pub/zajcsuk_2020_OGET.pdf
[c-4] Ambrus Zelei, Dóra Patkó: Alternative inverse kinematic calculation methods in velocity and acceleration level. Internation Conference on Dynamical Systems, Theory and Aplications (DSTA 2019), December 2-5, 2019, Lodz, POLAND.
https://www.mm.bme.hu/~zelei/zelei_pub/patko_2019_DSTA_CON191.pdf
[c-5] László Bencsik, Dalma Nagy, Ambrus Zelei, Tamás Insperger: The mechanical background of devices for balancing skill development. Theory and Aplications (DSTA 2019), December 2-5, 2019, Lodz, POLAND.
https://www.mm.bme.hu/~zelei/zelei_pub/bencsik_2019_DSTA_LIF192.pdf
[c-6] Ambrus Zelei, László Bencsik, Tamás Insperger, Gábor Stépán: Stable internal dynamics of a legged hopping model with locomotion speed control. The 15th IFToMM World Congress, Krakow, Poland, June 30 - July 4, 2019.
https://www.mm.bme.hu/~zelei/zelei_pub/zelei_2019_IFToMM.pdf
[c-7] Zana, R. R., Zelei, A.: Az Acroboter beltéri robot modellezése és térbeli mozgáskövetése pásztázó lézersíkok elvén. XIII. Magyar Mechanikai Konferencia - MaMeK, Miskolc, Hungary, 27-29. August, 2019.
https://www.mm.bme.hu/~zelei/zelei_pub/zana_2019_MaMeK.pdf

[c-8] Patkó, D., Zelei, A.: A poszturális egyensúlyozás és a futás stabilizációjához felhasznált energiamennyiség viszonyának becslése. XXVII. Nemzetközi Gépészeti Konferencia - OGÉT, Nagyvárad, Románia, 2019. április 25-28.
https://www.mm.bme.hu/~zelei/zelei_pub/patko_2019_OGET.pdf
[c-9] Zana, R. R., Zelei, A.: Swept Laser Based 3D Pose Detection of the Swinging Robot Acroboter. 18th Mechatronics Conference, Brno, Chech Republic, 5-7. Dec., 2018.
https://www.mm.bme.hu/~zelei/zelei_pub/zana_2018_Brno.pdf

6.3 Extended abstracts

[a-1] Patkó, D., Zelei, A.: Numerical Stability Analysis of the Conservative SLIP Model with a Hill-Type Muscle. ECCOMAS Multibody Dynamics Conference, Budapest, Hungary (online), December 12-15, 2021. (Extended abstract)
https://www.mm.bme.hu/~zelei/zelei_pub/patko_2021_eccomas.pdf
https://eccomasmultibody2021.mm.bme.hu/Files/EccomasMultybody2021_Abstracts.pdf
[a-2] Zajcsuk, L., Zelei, A.: Statistical Analysis of Performace Measures During Acceleration and Deceleration in Overground Running. ECCOMAS Multibody Dynamics Conference, Budapest, Hungary (online), December 12-15, 2021. (Extended abstract)
https://www.mm.bme.hu/~zelei/zelei_pub/zajcsuk_2021_eccomas.pdf
https://eccomasmultibody2021.mm.bme.hu/Files/EccomasMultybody2021_Abstracts.pdf
[a-3] Zana, R. R., Zelei, A.: Motion Control of a Crane-like Manipulator relying on the HTC Vive - Precision and Accuracy of the Pose Estimation. ECCOMAS Multibody Dynamics Conference, Budapest, Hungary (online), December 12-15, 2021. (Extended abstract) PDF, online
https://www.mm.bme.hu/~zelei/zelei_pub/zana_2021_eccomas.pdf
https://eccomasmultibody2021.mm.bme.hu/Files/EccomasMultybody2021_Abstracts.pdf
[a-4] Nagy, Á. M., Patkó, D., Zelei, A.: Discovery and Online Interactive Representation of the Dimensionless Parameter-Space of the Spring-Loaded Inverted Pendulum Model of Legged Locomotion Using Surface Interpolation. 16th International Conference on Dynamical Systems Theory and Applications (DSTA 2021), December 6-9, 2021 On-line (Accepted 2 pages extended abstract)
https://www.mm.bme.hu/~zelei/zelei_pub/nagy_2021_dsta21_abstract.pdf
[a-5] Zana, R., Zelei, A.: Experimental Evaluation of an Underactuated Inverse Dynamics Control Approach based on the Method of Lagrange-Multipliers. 16th International Conference on Dynamical Systems Theory and Applications (DSTA 2021), December 6-9, 2021 On-line (Accepted 2 pages extended abstract)
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[a-6] Zajcsuk, L., Zelei, A.: Correlation of Biomechanic Performace Measures with Acceleration and Deceleration in Human Overground Running. 16th International Conference on Dynamical Systems Theory and Applications (DSTA 2021), December 6-9, 2021 On-line (Accepted 2 pages extended abstract)
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[a-7] Habib, G., Bencsik, L., Insperger, T., Zelei, A.: Impacts Versus Non-Impulsive Muscle and Joint Loads in a Two-Segmented Model of Hopping. ECCOMAS Multibody Dynamics Conference, Duisburg, Germany, July 15-18, 2019.
https://www.mm.bme.hu/~zelei/zelei_pub/habib_2019_eccomas.pdf