**Riding waves with optimal control: A biomechanical analysis of surfing**

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**Summary**

We developed a motion analysis method for surfing based on optimal control simulations and sensor fusion. Simulations are created by solving an optimization in which muscular effort and a tracking error of inertial sensor and pose estimation data are minimized. We developed a contact model for the interaction between water and surfboard. The simulations revealed higher muscle activations in the front leg, consistent with accelerating and decelerating the surfboard, and higher joint moments in the rear leg, consistent with stabilization.

**Introduction**

Motion analysis in surfing is challenging due to the water environment, although it could provide athletes and coaches with valuable insights to improve performance and prevent injuries. For example, various environmental factors, such as the effects of higher waves, could be tested without putting surfers at risk. As surfing cannot be replicated in a motion laboratory, unrestricted sensor techniques are necessary. Recently, we developed an optimal-control based approach to analyze three dimensional (3D) movements by creating simulations from virtual inertial measurement units (IMUs) data [1]. Real sensor data is noisy and the sensor position and orientation on the body can slightly change over time, which causes inaccuracies in the simulation. To improve simulation accuracy, we present a sensor fusion approach, combining IMU data with deep learning-based human pose estimation (HPE) data for tracking [2]. Here, we show that we can reconstruct surfing using this sensor fusion approach and investigate the difference in joint moments and muscle forces between the front and rear legs.

**Methods**

We collected data from seven experienced surfers on an artificial river wave (Nürnberger Dauerwelle e.V.). We equipped the surfers with ten IMUs and placed RGB cameras around the wave. We estimated joint angles from 3D keypoints predicted through a finetuned HPE model [3]. IMU orientation was estimated through single-value decomposition based on the direction of gravity and sagittal plane calibration movements. To simulate surfing, we solved an optimal control problem for a 3D musculoskeletal model with 33 degrees of freedom and 92 muscles [1], in which a combination of effort and tracking error was minimized. The model was scaled to participants' height and weight. We created a contact model to estimate the forces between the water and the surfboard, inspired by [4]. To validate our result, we compared the simulated contact forces to those estimated directly from the sensors' accelerations. We then compared joint angles, joint moments, and muscle forces between the front and rear legs to investigate the contribution of both legs.

**Results and Discussion**

Our validation showed good agreement between simulated and estimated forces (mean RMSD ± standard deviation: 0.17 ± 0.09 body weight, correlation coefficient of 0.82). We found differences between peak rear and front leg joint angles and moments up to 47%. Muscle forces were in general higher in the front leg (Fig. 1). The higher force in the front leg muscles stemming from the acceleration and deceleration could be related to the task of maneuvering the surfboard, while higher joint moments in the rear leg could be related to stabilization [5].

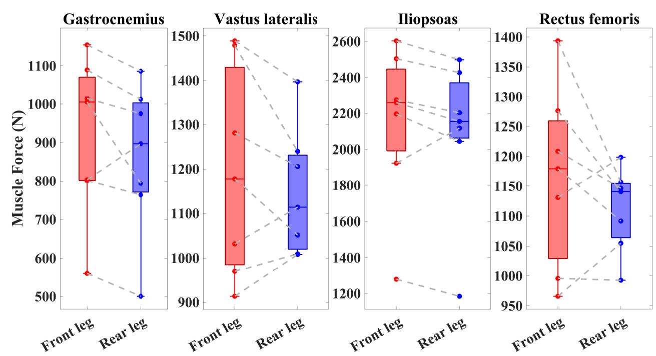


**Figure 1**: Muscle force comparison between front and rear leg over all seven participants.

**Conclusions**

We were able to perform biomechanical motion analysis of surfing through optimal control simulations that tracked a combination of IMU and HPE data. We showed that the front leg has higher muscle forces, while the rear leg has higher joint moments. In future, we plan to analyze surfing in the ocean using the RGB cameras and other additional sensors placed on the surfboard.

**References**

[1] Nitschke et al. (2024). *Front. Bioeng. Biotechnol.*, **12**:1285845.
[2] Pearl et al. (2023). *J. Biomech.*, **155**:111617.
[3] Zhu et al. (2023). *ICCV*, 15085-15099.
[4] Heinrich et al. (2022). *Front. Bioeng. Biotechnol.*, **10**:8945
[5] Borgonovo-Santos et al. (2021). *Sensors.*, **21(5)**:1783