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A PREDICTIVE SIMULATION FRAMEWORK FOR LEVER-PROPELLED WHEELCHAIR LOCOMOTION

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INTRODUCTION

The long-term use of pushrim-propelled manual wheelchairs can lead to upper extremity pain and injuries due to the large, repetitive upper extremity loads [1,2]. In order to reduce these effects, alternative propulsion modes have been proposed and investigated [2]. Among these solutions, the lever-propelled wheelchair is perhaps the most promising, providing variable mechanical advantages and biomechanically more favorable arm configurations [2,3].

In spite of the potential benefits of lever-propelled wheelchair locomotion, appropriate ranges of system parameters such as pivot location and gear ratio are still poorly known. This study aims at contributing to the future understanding of the effects of different system parameters on propulsion patterns and upper extremity loads by proposing a torque-driven model of the wheelchair-user system in lever-propelled wheelchair locomotion as well as a predictive simulation framework.

METHODS

The proposed model, Fig. 1, is a planar, moving four-bar linkage, representing an individual applying force in two levers coupled by gears to the rear wheels of a wheelchair. The model consists of four rigid bodies: arms, forearms, levers and body+wheelchair. The shoulder and elbow articulations, the lever pivot and the connection between arms and lever are considered ideal hinge joints. All anthropometric data were obtained from the standard Lower and Upper body Model available in the open-source software Opensim, scaled to a total body mass and a stature of 80 kg and 1.70 m, respectively.

The locomotion cycle was divided in two phases: the propulsion phase, with 1 degree of freedom (DoF), in which the lever is coupled through a fixed gear ratio to the rear wheels of the wheelchair, and the recovery phase, in which the lever is not coupled to the rear wheel, resulting in 2 DoFs. The transition between the return and the propulsion phases is assumed collisionless.

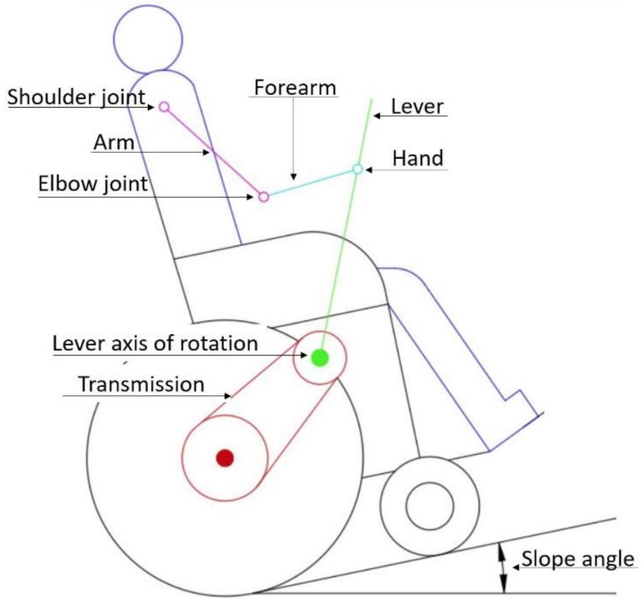

Fig 1: Proposed model of a lever-propelled wheelchair.

The predictive simulations resulted from the solution of an optimal control problem that searched for periodic optimal time histories of the generalized coordinates and velocities, elbow and shoulder torque, τ_S and τ_E, and phase durations, that minimized the quadratic objective function:

$$J = \int_0^{t_f} \frac{({\tau_S}^2 + {\tau_E}^2)}{t_f\,\bar{v}}\,dt,$$

and satisfied a prescribed average speed $\bar{v}$ = 0.5 m/s, the equations of motion and continuity conditions between phases. The problem was solved using the optimal control software PROPT (Tomlab Optimization Inc., Pulman, USA), which implements a Direct Collocation approach, with 50 nodes in each phase.

In order to illustrate the applicability of the proposed model and framework, simulations were generated for 4 combinations of slope angles and gear ratios, as shown in Table 1.

Table 1. Simulation scenarios.

Scenario	**1**	**2**	**3**	**4**
slope angle	0º	0º	4.5º	4.5º
Gear ratio	1:1	1:2	1:1	1:2

RESULTS AND DISCUSSION

Fig. 2 shows the predicted simulation patterns for scenario 3. In the propulsion phase, the lever moves forward, with application of positive work and acceleration of the wheelchair. As the upper limbs and levers are retrieved in the first half of the recovery phase, the wheelchair is first further accelerated due to mechanical coupling and then decelerated under the effect of the rolling resistance forces and weight component in the case of uphill locomotion.

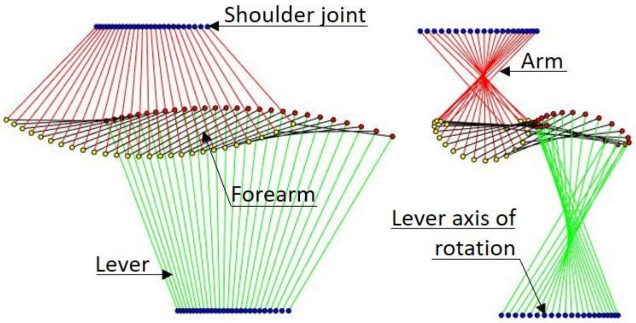

Fig 2: Stick figures of simulation in scenario 3 during the propulsion (left) and recovery (right) phases.

The simulation results show that lower gear rations lead to shorter propulsion lengths and higher cadences, on the level (Fig. 3) and on the 4.5º slope (Fig. 4), results which are consistent with experimental observations in [3]. It is important to observe that the lower gear ration does not lead to lower joint moments in the simulated scenarios, but to shorter propulsion phase durations instead.

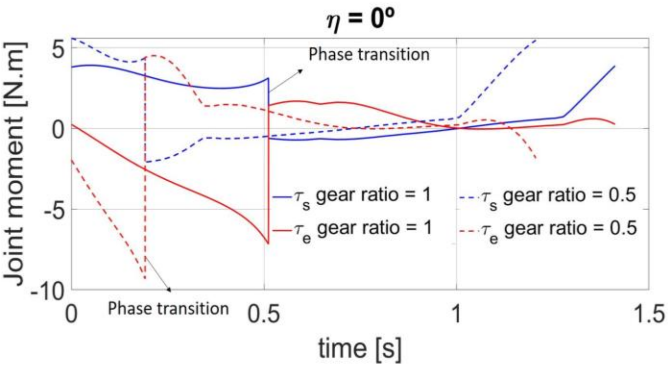

Fig 3: Shoulder and elbow moments for both gear ratios and inclination angle of 0º.

On the slope (Fig. 4), joint moments are larger, total cycle durations are shorter, and propulsion phase durations are longer compared to locomotion on a level surface (Fig. 3). Note that recovery phase joint moments on the slope are also much larger due to the high accelerations associated with the required fast repositioning of the upper extremity and levers.

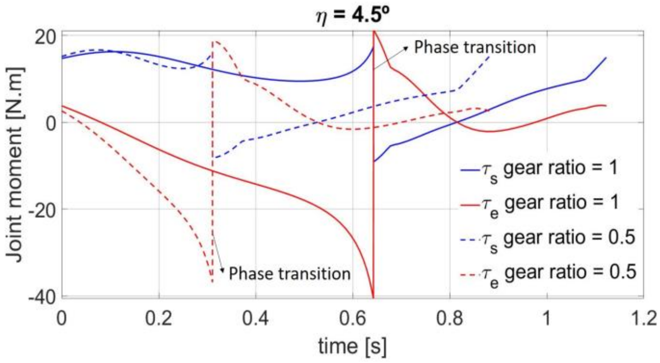

Fig 4: Shoulder and elbow moments for both gear ratios and inclination angle of 4.5º.

CONCLUSIONS

A predictive simulation framework was proposed for lever-propelled wheelchair locomotion that was shown to produce realistic predictions, consistent with available experimental observations reported in the literature. The results provide some preliminary insights into the effects of gear ratio and slope angle on lever-propelled wheelchair locomotion patterns.

The model used so far is torque-driven and does not consider the important influence of muscle properties. Future studies will incorporate muscles in the model and extend the investigation on the influence of wheelchair system properties on lever-propelled wheelchair locomotion.

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