Numerical simulations for improving wheeled mobility of manual wheelchair users among a set of daily-life activities

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Abstract: Manual wheelchair (MWC) locomotion is an exhausting task for the upper limbs. Hence, reducing energy loss can improve users' mobility. The purpose of this study was to investigate how numerical optimization could allow decreasing the energy loss (swiveling and rolling resistance) by numerically adjusting MWC settings, including seat height and anterior-posterior position, seat and backrest angles, and wheelbase. One participant performed a set of daily-life MWC maneuvers, including start-up, straight propulsion or u-turns using an instrumented wheelchair allowing handrims, seat, backrest and footrest forces and torques to be measured. These mechanical actions were used as inputs of a mechanical model to assess instantaneous values of rolling and swiveling resistances. This numerical model was parameterized with several settings, including fore-aft and vertical positions of the seat, wheelbase and seat/backrest angles. For each trial and each task, a numerical optimization procedure was designed and implemented in Matlab to find the configuration minimizing energy loss while ensuring no-tipping of the MWC. Numerical optimization allowed the total energy loss to be decreased. Optimal settings were different according to the trial and the task that was performed. This mobility improvement was reached at the expense of the overall stability. MWC settings optimization through numerical optimization allows defining a MWC configuration that would improve users' mobility by decreasing energy loss by rolling and swiveling resistance. This preliminary investigation should be completed with a musculoskeletal model of the upper limbs to generate optimal wheelchair locomotion taking into account shoulder loading.

Keywords: wheelchair, mobility, optimization.

Introduction

As manual wheelchair (MWC) locomotion is a strenuous task for the upper limbs (Mercer et al., 2006), it is believed that adjusting settings could be a helpful strategy to reduce the articular loading. Some studies have tackled this question experimentally by testing multiple wheelchair configurations and analyze the adaptations in the biomechanics of the locomotion, either for sports (van der Slikke et al., 2018) or daily-life applications. However, it is difficult to test the influence of several parameters simultaneously due to the high number of resulting configurations. Another approach to find optimal MWC configurations is to use numerical simulation. In this study, our main goal was to use optimization procedures to numerically investigate whether changes in several wheelchair settings (seat position, seat height, wheelbase, seat/backrest angles, and camber angle) could reduce the energy loss during a locomotion cycle, thus improving mobility. To fulfill this objective, we 1) developed a mechanical model of MWC to compute the ground reaction forces applied on the wheels, 2) collected experimental data (kinematics and kinetics) in various daily-life MWC tasks, 3) performed optimization procedures on the previously mentioned settings in the aim of minimizing energy losses due to rolling and turning resistance.

Methods

Mechanical model of the MWC

The MWC mechanical model was built, as an extension of previous work (Sauret et al., 2013) by expending the equations of motion, with several assumptions: translation and rotation were performed on a flat and horizontal surface, rear and front wheels rolled without sliding, the user was modelled as an overall set of mechanical actions, applied by the hands on both handrims and by the body on the frame of the MWC (seat, backrest, footrest), and finally rolling and swiveling resistances were not neglected for rear and front wheels. The resulting set of equations enabled to compute the instantaneous values of the normal and transversal components of the ground reaction forces, as functions of both the MWC parameters (settings, masses, inertias, etc.) and the mechanical actions exerted by the user. The normal components of these reactions were then used to compute the energy loss by rolling and swiveling resistances.

Experimental data

One participant performed a set of daily-life MWC maneuvers, including start-up, straight propulsion or u-turns using an instrumented wheelchair (Dabonneville et al., 2005; Sauret et al., 2013; Hybois et al., 2018) allowing handrim, seat, backrest and footrest forces and torques to be measured.

Optimization procedure

With the assumption that mechanical actions remained unchanged when settings were modified, the MWC model allowed us to numerically alter some settings of the MWC and compute the resulting energy losses. The settings allowed to be modified in the optimization procedure were seat anterior (x_s) and vertical (y_s) positions, wheelbase (w_b), seat (θ_s) and backrest (θ_b) angles, camber angle (θ_c). These six parameters were the variables of our optimization procedure. The objective function was the total energy loss by rolling and swiveling resistances per cycle, formulated as a time integration over the whole task. We added constraints to increase the feasibility of the solutions. A path constraint enforced the stability index (distribution between front and rear normal components of the wheel/floor reaction forces) to remain in a no-tipping range at any moment. Another constraint was added, to guarantee that the MWC configuration at each iteration of the optimization was physiological, i.e. allowing a grip of the handrims and contact of the feet on the footrest while seated. This optimization procedure was applied to several cycles of daily-life tasks: steady-state propulsion, start-up and turning maneuver.

Results

The optimization procedure allowed to reduce the energy loss for most cycles in each task, at various scales. With respect to the default stable MWC configuration, the optimal settings led to a reduction of energy loss per cycle of 25 ± 5 % for propulsion, 22 ± 9 % for start-up and 14 ± 7 % for turning maneuvers. However, as shown on Fig.1, the optimal settings could vary for a single task, depending on the cycle, which underlined the sensitivity of the method to experimental data.

However, some trends can be observed for some settings. Mobility seems to be improved for backwards positions of the seat x_s and for the highest values of wheelbase w_b.

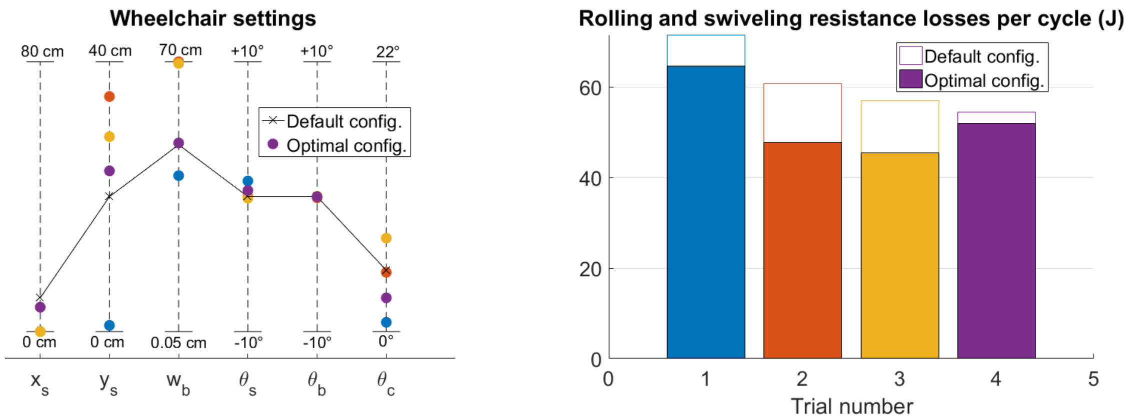

Figure 1. Optimal wheelchair settings and reduction of energy loss for a typical subject, for the turning task. Each color is associated with a single trial.

Conclusion and discussion

The numerical approach developed in this study showed its ability to minimize energy loss during MWC locomotion tasks. A method based on this simulations could improve wheeled mobility and be a first step towards an additional tool for occupational therapists when prescribing a wheelchair. However, there are still many improvements to be done. Indeed, for the same task, optimal settings vary from one cycle to another, hindering general recommendations to be made. This is due to the sensitivity of the methods to experimental inputs. The next step of this work would be to overcome these limitations, either by considering average cycles for each task, or by replacing experimental data by simulated ones, using optimal control strategies. Other optimization objectives, such as minimizing shoulder loads or maximizing MWC velocity could also be investigated.

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