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Optimising Elbow Flexion Exosuit Design: Considering Metabolic Cost and Interaction Forces

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1. Introduction

For rehabilitation or assistance applications, a new class of wearable devices called 'soft exoskeletons' or 'exosuits' emerged this last decade. Exosuits are lightweight with compliant material, soft actuators and respect of biological joints (Xyolannis et al, 2022). The design of these devices is challenging, particularly in terms of cable routing and physical human-robot interactions, which impose safety and comfort criteria (Rocon et al, 2008). Literature reveals various approaches ranging from bioinspired methods to optimization aimed at reducing contact forces or ensuring human workspace (Lu et al, 2023). Then energy savings for users are assessed experimentally using prototypes (Xyolannis et al, 2022). This study aims to implement a human model wearing a cable-driven exosuit in a closed loop simulation and optimise placement of cable anchors considering metabolic cost and interaction forces. In this way, safety constraints are met and energy expenditure is quantified before creating a less energy-consuming device.

2. Methods

To conduct multi-criteria optimisation, the arm model, simulation methods, as well as acceptable force limit values considered are outlined below.

2.1 Musculoskeletal model

Musculoskeletal model is developed with OpenSim, a widely used open source software (Delp et al, 2007). The chosen model, 'arm26', is an upper limb model with two degrees-of-freedom (DoF) (shoulder elevation and elbow flexion) and six muscles. To integrate the exosuit, two cylindrical rigid bodies are added: one cuff embedded to the humerus (length: $l_{\text{cuff}} = 0.1$ m; radius: $r_{\text{cuff}} = 0.0375$ m) and one cuff embedded to the radius/ulna group (length: 0.1 m; radius: 0.0292 m), along with one cable allowing elbow flexion with anchors at each cuff. Finally, a dumbbell mesh simulating a load is placed in the hand.

2.2 Human in the loop simulation platform

The simulation platform is implemented in MATLAB and incorporates OpenSim features via its Application Programming Interface. It follows the framework presented by Sambhav et al. 2022. The input are cable anchors and a trajectory: an elbow flexion from 0 to $\pi/2$ in one second described by a sinus signal. The outputs are metabolic cost ($\dot{E}$) and angular position. A gravity compensation control law computes cable tension and knowing its direction, the projection along the normal and tangential axes gives normal and shear forces.

2.3 Safety and constraints on interaction forces

Pain pressure threshold

Algometry literature assures that humans feel discomfort and pain around 25kPa for circumferential compression (Kermavnar et al, 2018). Assuming the cable can only pull, pressure is distributed around the posterior side of cuffs. Maximal peak of normal force $\overrightarrow{F_N}$ is constrained such as:

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$$\left\|\overrightarrow{F_N}\right\| \leq 25.10^3 . \frac{l_{cuff}(2\pi r_{cuff})}{2}$$

No slipping conditions

When a cuff applies continuous pressure on human body, the limit pressure is 4kPa (Rocon et al, 2008). 3.5kPa is a comfortable compression level. Assuming well-distributed forces, to avoid slipping on the skin the tangential force must guarantee Coulomb's law:

$$\left\|\overrightarrow{F_{cuff}}\right\| . \mu \geq \left\|\overrightarrow{F_T}\right\|$$

$$with \left\|\overrightarrow{F_{cuff}}\right\| = 3500 l_{cuff}(2\pi r_{cuff})$$

$\left\|\overrightarrow{F_{cuff}}\right\|$ is the force required to hold the cuff in place and μ is the coefficient of friction between skin and cuff, equal to 0.6 (Sanders et al, 1998).

2.4 Optimisation strategy and Objective functions

The design of the exosuit must minimise the effort and the forces on the forearm. Let $\dot{E}_{exo,i}$ and $\dot{E}_{noexo,i}$ be metabolic costs with and without exosuit. Thus, two objective functions are defined as follows:

$$\begin{cases} f_1 = \frac{1}{n}\sum_{i=1}^{n} \frac{\dot{E}_{exo,i}}{\dot{E}_{noexo,i}} \\ f_2 = \frac{1}{n}\sum_{i=1}^{n} \left\|\overrightarrow{F_{N,i}} + \overrightarrow{F_{T,i}}\right\| \end{cases}$$

with n number of time steps.

Multiobjective optimisation: NSGA-II

To solve this multi-objective problem, NSGA-II (Deb et al, 2002) is set up on MATLAB. An individual consists of six genes: three Cartesian coordinates for each anchor points in respective cuff's frame. Moreover, the parameters are restricted to fit the anterior side of cuffs. Computations involve a population of 60 individuals and 100 generations.

3. Results and discussion

According to the Pareto front (Figure 1), the exosuit reduces the metabolic cost by 36% on average, but cable routing has a greater influence on shear and normal stress. The solution producing the lowest forces is a cable anchored at the top of the arm cuff and at the bottom of the forearm cuff where the force direction is in the same plane as the movement.

If weight is added, the exosuit will fully compensate the load with the gravity compensation controller, optimal solution that minimizes forces will be the same, but the force limits defined previously will no longer be respected (Table 1). A way of dealing with could be to include an assistance rate in the control law. For example, assistance of 30% for a 5kg load saves 23% of energy with a reasonable shear force of 39N.

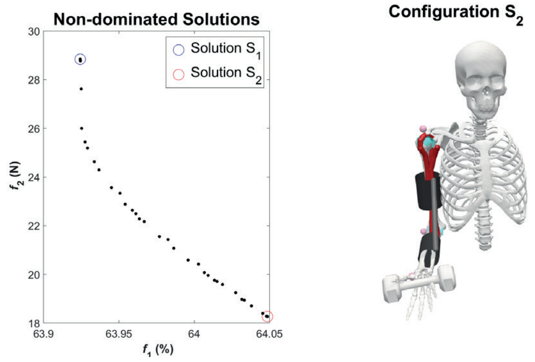

Figure 1. Multiobjective optimisation results.

a) Pareto front b) S_2 actuator configuration

Table 1. Mean metabolic savings and forces with the optimal solution S_2 for different loads.

Outputs	m=0kg	m=2kg	m=3kg	m=5kg
$100 - f_1$	36 %	63 %	68 %	68 %
$max\left\|\overrightarrow{F_N}\right\|$	14.2 N	45.3 N	60.4 N	89.3 N
$max\left\|\overrightarrow{F_T}\right\|$	19.9 N	64.3 N	86.5N	131.0N

4. Conclusions and perspectives

This work presents the optimisation of the design of an exosuit for elbow flexion according to 2 criteria, energy expenditure and forces applied on the upper limb. They are evaluated with a simulation platform and optimised using NGSA-II. According to simulations, cable placement plays a more important role in force distribution. The results are promising, showing a 36% reduction in metabolic cost with exosuit and a 37% average decrease in interaction forces between solution S_1 and S_2. However, to design a complete exosuit with all DoF for shoulder and elbow, further studies must be conducted, including movements that demand additional DoF and cables and using a more thorough musculoskeletal model like the 'MoBL-ARM' (Saul et al, 2015).

Conflict of Interest Statement

All authors declare they have no conflicts of interest.

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