Optimizing Force Transfer in a Soft Exoskeleton Using Biomechanical Modeling

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Abstract. A newly developed prototype of a soft cable-driven elbow exoskeleton for lifting and lowering of loads was developed. To identify potential harmful forces within the elbow joint, an analysis was conducted with biomechanical simulation. To analyze the effect of the exoskeleton on the human body, biomechanical simulations were conducted on the prototype to assess the joint reaction forces during a lifting task with and without the soft elbow exoskeleton. To reduce these forces, the optimal way to attach the cables for generating the moment around the elbow needs to be identified using biomechanical simulation. First results show that in average the load on the elbow joint is reduced while wearing the exoskeleton compared to lifting 5 kg without any assistance. A large distance between the lower arm and the attachment point in ventral direction is very beneficial, due to the introduction of another lever arm into the system. Especially if the elbow is fully stretched, whereas the pulling force vector would go parallel to the arm. With the implementation of the lever arm, the load on the elbow is lower for any position of the arm.

Keywords: Exoskeleton · Biomechanical simulation · Force optimization · Force analysis

1 Biomechanical Simulation in the Design of Exoskeletons

1.1 Motivation

The primary goal of exoskeletons for industrial applications is to reduce the load on the person using the system during physical straining tasks. Especially with active exoskeletons it is a concern that misalignments between the human biomechanics and the exoskeleton kinematic cause shearing forces and high loads in the human joints. This remarkably reduces their benefit and justification [1]. So in the design of exoskeletons those forces need to be considered and avoided in very early stages of the development [2]. These considerations are especially important for soft exoskeletons, since they do not contain rigid structures that can divert forces away from the human body.

Commonly used tools in literature for these early stage analyses are biomechanical simulations. They are used to investigate the muscular or joint load during specified

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movements to detect the intended reductions as well as unintended increase of strain on the human body. Similar to these approaches a new design for a soft cable-driven exoskeleton will be analyzed for efficiency and freedom from damaging forces.

Furthermore, a design optimization is performed to improve the force flow though the human body and identify the configuration with the minimal amount of strain on the joints.

1.2 Design of the Soft Exoskeleton

The design of the soft cable-driven exosuit is described in detail in [3]. Its intended use is the support of the flexion of the human elbow during lifting tasks. To do so, a cable is led through a tubing system along the lateral as well as the medial side of the upper and lower arm with a loop at the wrist [3]. The torque is induced around the elbow by the cable detaching shortly in front of and behind the elbow at the upper and lower arm. The motor for pulling the cable is located at the back of the exoskeleton. The course of the cable on the medial side is sketched in Fig. 1, the lateral side where the cable loops back is identical and therefore obscured in the figure.

A preliminary kinematic analysis shows a force vector pointing into the elbow and therefore potentially increasing the joint interaction forces which could lead to a damage in the joint with long term usage. The biomechanical simulation is needed to show, if these considerations are true or if a reduction of strain on the elbow joint can be achieved by the soft exoskeleton.

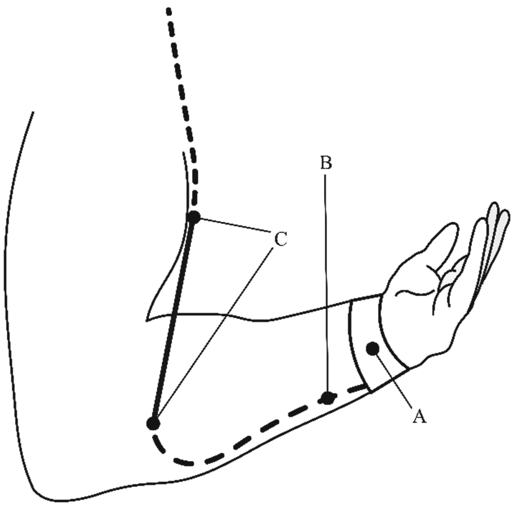

Fig. 1. Representation of the cable path running though the sleeve of the exoskeleton on the medial side. **A** represents the wrist cuff where the cable is looping though to the lateral side, **B** shows where the cable is lead through the tube; **C** are the two points where the cable leaves the tube on both sides of the arm.

2 Methodology

For this biomechanical optimization and analysis, the simulation software "OpenSim 4.0" made by SimTK was chosen.

Based on the method for simulating and modeling exoskeletons that are presented in [4] for the software "OpenSim" and the general approach for a model based optimization loop as described in [5], the simulation and optimization method is conducted in this project. In a similar way a similar exoskeleton but with rigid shells and spring-loaded actuation was optimized in [6].

The biomechanical model is based on the "Arm26" [7] model which was adapted to only include the muscles relevant to the elbow flexion and extension. It consists of triceps brachii modelled as three separate muscles, the biceps brachii, the brachialis anticus, anconeus muscle and the biceps brachioradialis.

The flexion movement was implemented in a way that only the elbow is flexed and extended from a fully stretched position at 0° to 145° and back. This represents the full range of movement in average for a person working in logistics [8]. The full movement takes 7.4 s with an average velocity of 39.14 °/s. The data was originally taken from a preliminary study published in [9] where loads were lifted in a similar setting as it is intended for the soft exoskeleton. It was adjusted to fit the whole movement of the arm with realistic accelerations, which results in an artificial dataset based on real life observations. The resulting curve for the degree of flexion over the time of movement is illustrated in Fig. 2.

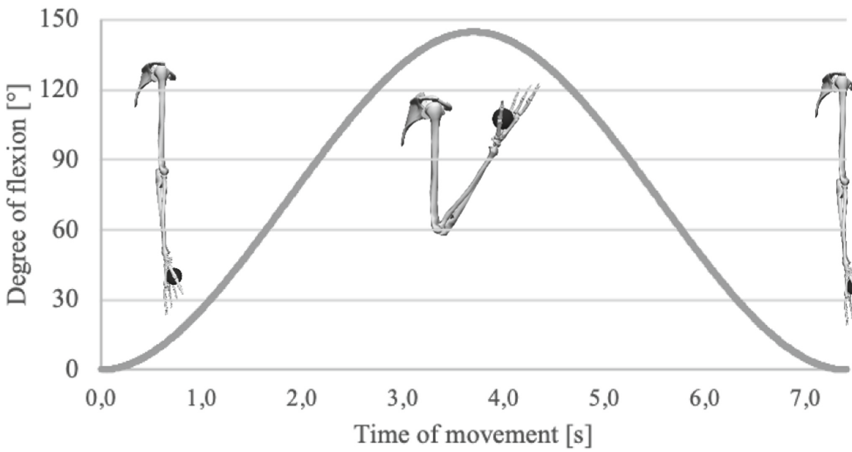

Fig. 2. Flexion angle of the elbow from 0° to 145° and back over movement duration of 7.4 s (artificial dataset based on real life observations from [9]).

For the first kinematic analysis in [3] two cable strands pulling lateral and medial at the lower arm were consolidated into one strand that it is applying the full force in the middle of the ventral side of the limb. So not the entire course of the cable is represented, only the part that is exposed between the two attachment points C as shown in Fig. 1.

The same approach is used in the biomechanical simulation to reduce the complexity of the optimization process. The target of the optimization is the minimization of the joint reaction forces by varying the attachment point on the forearm. The position of this attachment point is variated in two directions, along the arm and perpendicular to the surface. All iterations of these variables are tested for a lifting load of 5 kg with one arm and the optimal configurations are determined.

The tendon of the exoskeleton is simulated by a path actuator originating at the top of the humerus, is guided parallel to the bone of the humerus by a path point and in the end is connected to the forearm in a straight line.

The weight of the load is implemented with a simple ball geometry that is connected to the hand of the model and given the weight of 5 kg. Figure 3 is the final model for the biomechanical simulation.

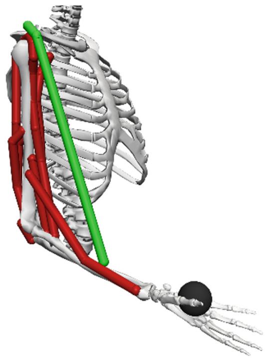

Fig. 3. Green: tendon-driven exoskeleton represented as a path actuator, red: triceps brachii, biceps brachii, brachialis anticus, anconeus, biceps brachioradialis muscles, black: lifting load.

After the model is completed, the simulation is executed using static optimization (SO) tool by OpenSim which is based on inverse dynamics to generate movement. It calculates the muscle forces by minimizing the sum of squared muscle activations.

To calculate the joint reaction forces (JRF) OpenSim provides a joint reaction analysis (JRA) tool [10]. With the JRA the joint forces are calculated based on all loads acting on the model, which includes contributions by joint structures like cartilage contact and omitted ligaments.

For the optimization the attachment point was changed in discrete values of 2 mm along the y axis and 1 mm along the x axis resulting in 144 positions that run though the simulation and the JRF is calculated for. Of those 144 positions 45 are excluded, since they are not viable for designing the exoskeleton, since the attachment point would collide with the upper arm during the elbow flexion. The remaining attachment points are presented in Fig. 4.

For the analysis of the resulting datasets, first a baseline simulation without the exoskeleton was conducted.

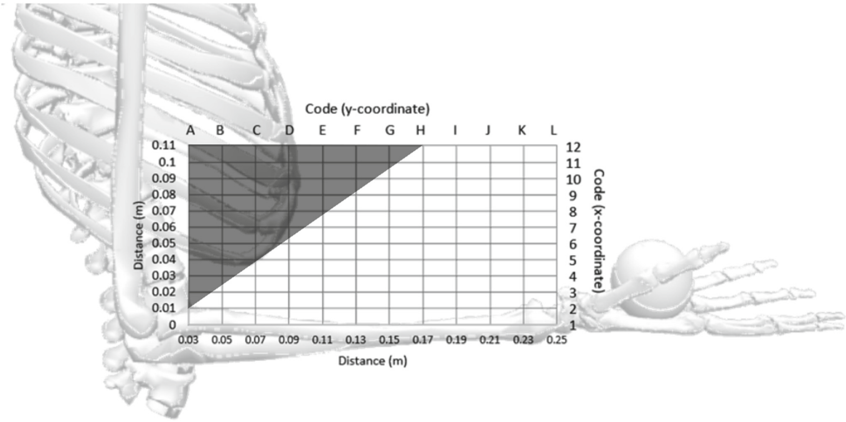

Fig. 4. Representation of the discrete attachment points used for the design optimization. The grey area marks the points that were removed from the dataset since they are not viable in a real exoskeleton.

3 Results

For the analysis of the exoskeleton the relevant output parameters of the JRA are the force x-, y-, and z- components of the JRF and their root-sum-of-squares (RSS), indicating the resulting force on the elbow. The co-moving coordinate system for the lower arm is shown in Fig. 5.

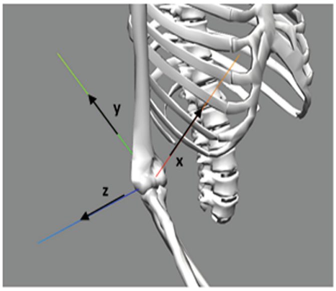

Fig. 5. The co-moving coordinate system for the lower arm.

In the case of the presented exoskeleton F_y is the potentially damaging force component, that may increase the compression of the joint tissue. Therefore, the RSS and the F_y are the two variables, that are compared for each variation of the attachment point and with the baseline.

The results for the baseline without the exoskeleton are for the largest peak in absolute values 419 N for F_y and 499 N for the RSS.

The results for the simulations with the different attachment points are clustered into two groups, one where the JRF are higher than the baseline and one group where the JRF are lower than the baseline. Those attachment points with lower forces than the baseline are clustered further, since they fulfill the minimum safety requirement that the forces are not increased by the exoskeleton usage. They are clustered into four areas of equal force ranges that are indicated in different shades in Fig. 6 and with ranges of 87 N for F_y and 106 N for the RSS. The absolute values for the thresholds between those areas are described in Table 1.

Table 1. Threshold forces for each cluster.

	C1 [N]	C2 [N]	C3 [N]	C4 [N]
Peak Fy	71–158	–245	–332	–419
Peak RSS	77–182	–288	–394	–499

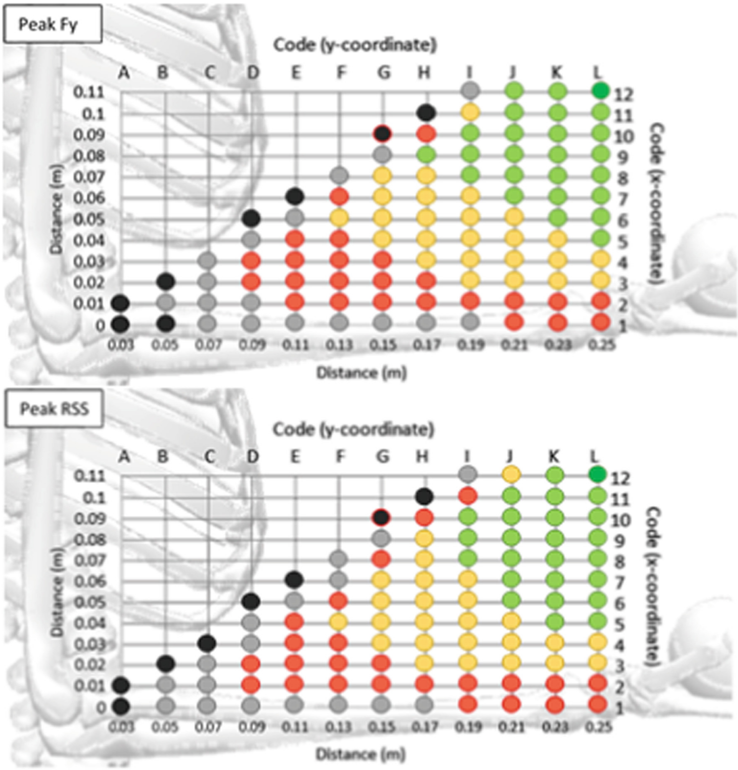

Fig. 6. Isometric force ranges for the F_y and the RSS peak forces. Black: higher than baseline, gray: C4; red: C3; yellow: C2; green: C1.

4 Discussion

The exoskeleton as described can decrease the joint load dramatically depending on the attachment point on the lower arm. There is a conflict between the optimal load and a feasible attachment point. To achieve the lowest joint reaction forces the attachment point needs to be as distal and ventral as possible. This results in a bulky construction that will find low acceptance with the users. To be convenient the attachment needs to be as proximal and as close to the arm as possible. Future studies need to evaluate where an optimum is, that satisfies both aspects sufficiently. However, there are only a few cases in Fig. 6, where the exoskeleton does not lower the joint load compared to lifting without exoskeleton.

While the reduction of joint reaction forces is a positive aspect, a second phenomenon manifests in the simulation. The direction of the RSS during the movement changes when wearing an exoskeleton compared to lifting without exoskeleton. This might damage the joint and it is to be evaluated in future studies if the reduction of the forces outweighs the change in directions. In Fig. 7 this phenomenon is demonstrated for the baseline without the exoskeleton and the attachment point 12K.

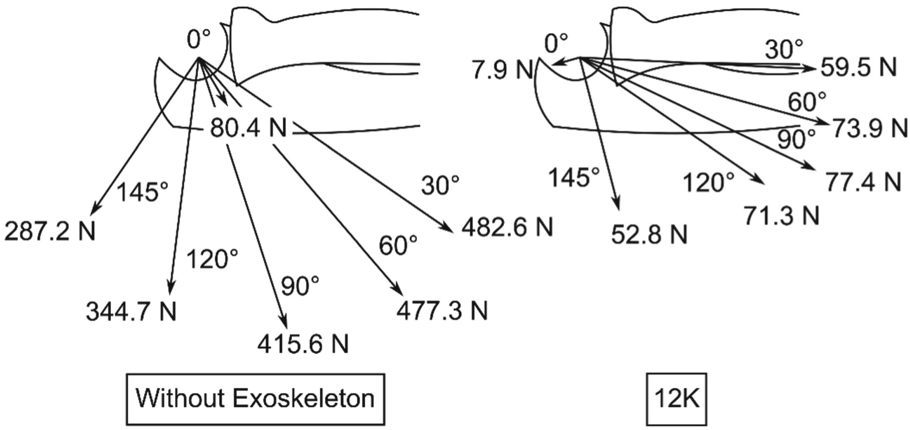

Fig. 7. Changing directions of the RSS vectors between the baseline without the exoskeleton and the attachment point 12K.

Limitation of the used model is the simplification of the bone structures in the forearm, which were consolidated into one rigid element, instead of ulna, radius and the hand separately. Also the gripping of the hand was not simulated and therefore a potential effect on the JRF due to the resulting muscle contraction in the forearm is not included.

In future work, similar to the presented method, a simulation and optimization of the attachment point of the upper arm needs to be done to achieve an optimization of the complete system.

Since simulation models are only an abstraction of the real word, the simulation results need to be validated. For that purpose, a test bench resembling the simulation setup will be constructed to validate the presented data.

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