Design and Optimization of the Thigh for an Exoskeleton based on Parallel Mechanism

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Abstract

A full parallel mechanism is suggested as a base construction for an exoskeleton to implement complex movement of body parts of the human relativ to each other. The optimal design of such a structure for a thigh is presented. The positions of the connection points of the linear actuators to the moving platform were chosen as design parameters. The calculation of these design parameters was perform numericaly. The results show that the designed parallel mechanism allows arbitrary motion of the thigh in a workspace of the mechanism which is large enough not only for walking but also for more complex movements like sitting down on a chair and standing up.

1 Introduction

This paper deals with the design and optimization of the legs for an exoskeleton. The goal is to design a mechanical structure for a leg which can support a disabled person in walking as well as performing complicated movements like sitting down and standing up.

In spite of the number of interesting applications for an exoskeleton like support for disabled people, rehabilitation, force amplification in space or underwater suits, only few research groups and research projects have worked on this topic recently. One of the reasons is the complexity of the mechanical construction. For real application, the structure which is attached to the parts of the human body should provide enough degrees of freedom and free space for the movement of body parts. Natural walking and performing movements like sitting down and standing up require the mobility of leg structures which is comparable with the mobility of a human leg. This requirement is important not only for comfort but also for stability. The hip joint (see Fig. 1) and the movement abilities of the thigh play a crucial role here. This joint is composed of three rotation axes each of which is indispensable for walking. The realization of the two axes X and Y in traditional way with serial kinematic chains usually composed of rotary actuators is complicated but possible. The problem lies in the third axis Z which goes through the thigh and cannot be implemented in this way.

The solution proposed in this paper is to use a fully parallel mechanism for implementation of the hip joint. The scheme of the suggested construction is shown in Fig. 2. The base of the parallel mechanism is fixed on the hip part of the trunk and the moving platform on the thigh close to the

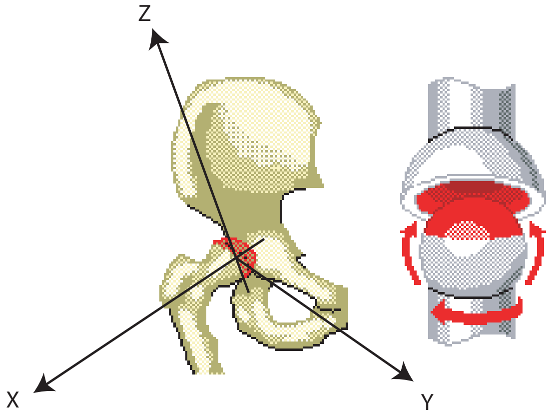

Figure 1: Hip joint and the required rotation axis for the thigh

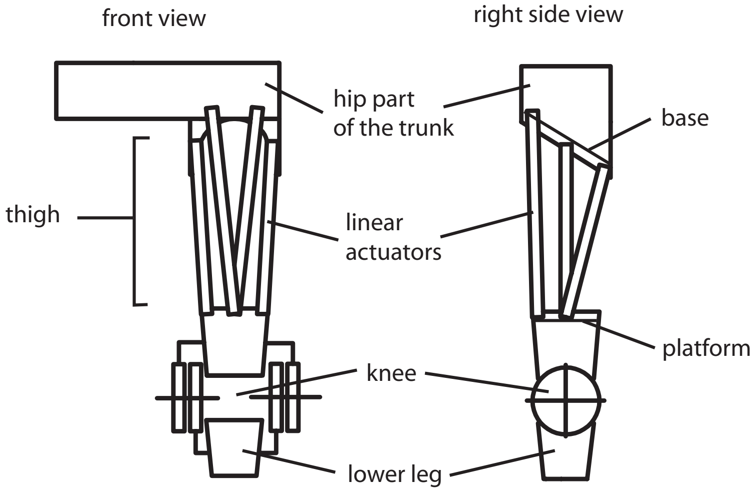

Figure 2: Scheme of the mechanical construction for the leg (thigh) of the exoskeleton

knee. If the base and platform are connected with six actuated kinematic chains, the platform and, therefore, the thigh have six degrees of freedom with respect to the base or the hip.

In this paper, the design and optimization study of the suggested construction is presented. The design process was carried out as follows. The needed workspace was calculated from measurements on the human body. The connection points of the actuators to the base (hip) were determinated in a way which would enable a disabled person to walk and to sit down on the chair (section 2). The connection points to the platform (knee) were calculated in an optimization process (section 3). The goal of the optimization was avoidance of architecture singularities [1] in the workspace of the parallel platform which automatically yields the enhancement of such important criteria of the construction as the reduction of forces in actuators and better performance in terms of achievable velocities and accelerations. After the determination of all connection points, the viability of the resulting structure is proved (section 4).

For the solution of the optimization problem, the numerical approach was used. The formulation of the cost function and advanced symbolic calculation before the optimization process allowed the fast and stable computation of the actuator connection points on the platform.

In this work, the results of the referenced papers were used, in particular the results of [2]. In contrast to [2], rather than the parameters of the given shape of the platform, this shape itself (considering practical constraints) was calculated in the optimization process.

The contribution of the paper is the introduction of the parallel mechanism as a basic structure for exoskeletons, the determination of an optimal design for this application and demonstration of the practical viability of the suggested construction.

2 Problem Formulation

The workspace of the parallel mechanism was determined by measurements on human bodies in order to allow walking, sitting down and standing up. Fig. 3 shows the scheme of the kinematic structure and the workspace of the thigh. The reference point C of the platform coordinate frame $F' = (C, X', Y', Z')$ should be able to move on the sphere surface with the center in hip joint O which is also the reference point of the base coordinate frame $F = (O, X, Y, Z)$. The area of motion is given by sweeping with the radius vector OC between the angles of $60°$ in sagittal and $30°$ in frontal plane of the human. The rotational part of the workspace was set to $10°$ around axes X' and Y' and to $30°$ around axis Z'.

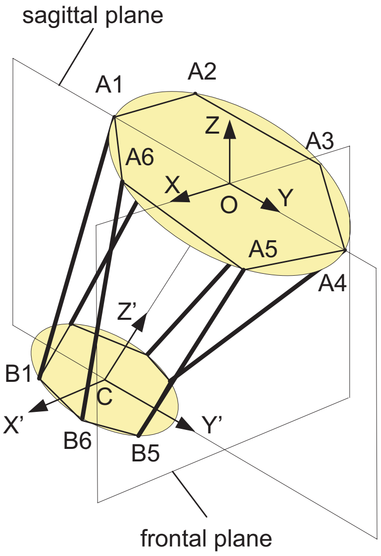

Figure 3: Scheme of the parallel mechanism

The design goal is to determine proper connection points for the actuators. It can be shown that the place of the connection points is crucial for the performance of the structure [3, 2]. In case of the exoskeleton, maximal actuator forces for defined loads and maximal achievable velocities as well as accelerations in the predefined workspace are most interesting characteristics. The minimization of forces in actuators allows to reduce the size and weight of the construction, maximization of the allowed velocities and accelerations at the end-effector lets more freedom in design of stabilization control for walking. In general, all of the connection points, $6 * 3 = 18$ parameters, have to be determined in the design process.

In this study the connection points of the base were set by combining results from other studies with requirements of the application area. The results presented in [2] show that parallel robots with triangular base and platform show better performance than the three other presented shapes. The triangular base with equal sides was selected as a starting point and modified in order to let the space at the back of the human free from mechanical parts which would allow the human to sit down as well as to stand on parallel legs. The resulting shape of the base is shown in Fig. 4.

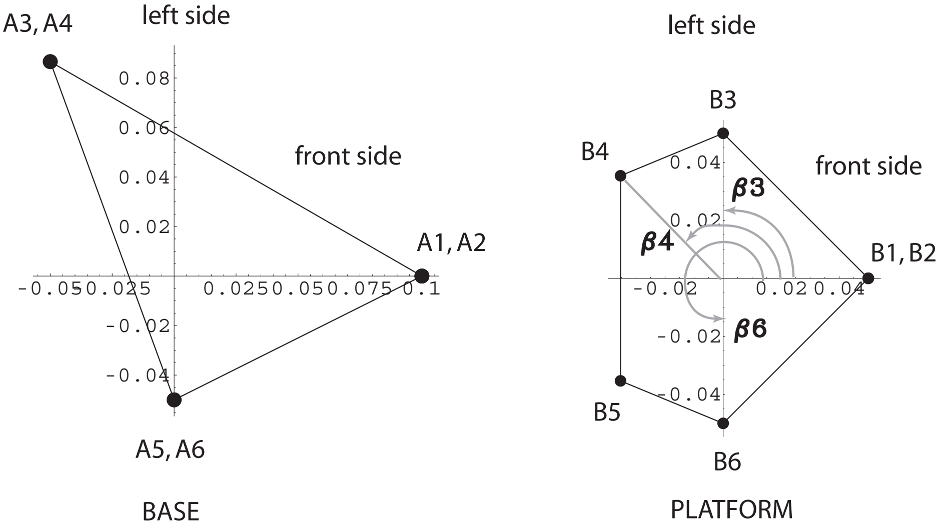

Figure 4: Shapes of the base and platform for thigh structure

Because of the application requirements, it was imposed that the connection points of the platform lie on a circle. Two points of the platform, B_4 and B_5, were fixed to provide enough free space in the back of the leg. The places of the points B_1, B_2, B_3, B_6 on the circle or the angles $\beta_1, \beta_2, \beta_3, \beta_6$ (see fig. 4) have to be found in an optimization process and are our design parameters.

Let $X = [x, y, z, \alpha, \beta, \gamma]^T$ denote the position and orientation of the mobile frame F' in frame F and $Q = [q_1, q_2, \dots q_6]^T$ the joint coordinates (actuator lengths). It is known (see e.g. [3]) that the relation between joint velocities $\dot{Q}$ and twist $\dot{X}$ of the frame F' is linear and given by the Jacobian matrix J of the parallel mechanism:

$$\dot{Q} = J\dot{X} \tag{1}$$

The Jacobian matrix is constructed from unit vectors along the linear actuators $n_i = A_iB_i / \|A_iB_i\|$ and vectors B_iC expressed in the base frame F:

$$J = \begin{pmatrix} n_1^T,\ (n_1 \times B_1C)^T \\ n_2^T,\ (n_2 \times B_2C)^T \\ \vdots \\ n_6^T,\ (n_6 \times B_6C)^T \end{pmatrix} \tag{2}$$

The investigation of the performance of parallel mechanism is based on a property study of the Jacobian matrix J. Indeed, eq. (1) shows that if the matrix J is singular in some points or subspaces of the workspace there will be some directions in which the platform can move without changing the actuators lengths or in which no movement is possible. The transpose of the Jacobian matrix J

is the force transformation matrix H that maps linearly the actuator forces to the forces and torques exerted on the end-effector (see e.g. [3]). This means that in case of a singular or ill-conditioned matrix J or H, the actuators will be not able to hold an arbitrary load or the forces in actuators will be immense.

The goal of the optimization is, therefore, to choose design parameters in a way, that the Jacobian matrix J is "as far as possible" from the singularities. This distance to the singularity of a matrix can be measured with a scalar cost function $\kappa = \kappa(J)$ which can be defined in different ways. It has to be noted that the matrix J depends not only on design parameter but also on pose X of the moving platform.

The problem for computation of design parameters yielding enhanced performance of the thigh structure can be formulated as the minimization of $\kappa(J)$, subject to constraints employed to prevent the crossing of actuators.

3 Solution of the Optimization Problem

In this work the cost function was defined as follows:

$$\kappa(J) = -\left| \det \begin{pmatrix} j_{11}/\alpha_1 & \cdots & j_{16}/\alpha_1 \\ \vdots & & \vdots \\ j_{61}/\alpha_6 & \cdots & j_{66}/\alpha_6 \end{pmatrix} \right| \tag{3}$$

where the α_i are the lengths of the row vectors of the matrix J:

$$\alpha_i = \sqrt{j_{i1}^2 + j_{i2}^2 + \cdots + j_{i6}^2}$$

It can easily be shown (see e.g. [4]) that the absolute value of the function $\kappa(J)$ in (3) is equal to the volume of the parallelepiped built from the unit row vectors of the Jacobian matrix J. In case of singularity at least one dimension of this parallelepiped vanishes and the volume shrinks to 0. In case of mutual orthogonality of the row vectors the cost function $\kappa(J)$ takes its smallest value -1.

The closed form of the expression (3) was computed using the symbolical computation software MATHEMATICA.

In other papers the condition number of the Jacobian matrix $cond(J) = ||J|| \, \left\|J^{-1}\right\|$ is used as a cost function. The cost function (3) is smoother than the condition number and yields better stability of the algorithm.

The optimization toolbox in Matlab has been used for the numerical optimization. As in [5] the optimization of the design parameters was performed for a representative pose X of the platform. After that, several configurations in the workspace were proved to be non singular.

4 Result

For the start solution, the following values of the design parameters can be taken: $\beta_1 = \beta_2 = 0$, $\beta_3 = \pi/2$, $\beta_6 = 3\pi/2$. The corresponding shape of the platform is shown in Fig. 4. The obtained solution was: $\beta_1 = \beta_3 = 60.17°$ and $\beta_2 = \beta_6 = 299.5°$. Fig. 5 shows the corresponding optimal shape of the platform and Fig. 6, the isometric projection of the whole mechanism. Significantly the determined solution is minimal for a quite large neighbourhood in the design parameter space, so changing the values of start solutions leads to the same solution of the optimization problem. An interesting point is also that despite quite high perturbations in the given base shape apart from equilateral triangle, the optimization procedure tends to form the triangle in the platform even though infinite varieties of shapes are possible. In [2] the triangle shape of the base and the platform were chosen intuitively and proved to be the best one among others three shapes. The results here support the strong assumption that the triangle shape is the best among all possible coplanar shapes for parallel mechanisms with six parallel legs (in the literature called general robot) without leg crossing. In the case where leg crossing was allowed, the calculated solution was: $\beta_1 = -91.68°$, $\beta_2 = 88.18°$, $\beta_3 = 43.48°$, $\beta_6 = -29.33°$ and the value of the cost function was improved to approximately 39%.

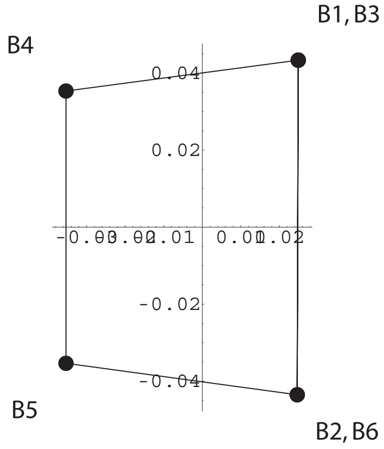

Figure 5: Optimal shape of the moving platform

The compound joints at the base and at the platform have to be split so that a practical implementation of the structure becomes possible.

It is possible to include more design parameters in the optimization procedure than presented in this paper. For example, one can allow the points B_1, B_2, B_3 and B_6 to lie not only on the circle but in the entire plane or even in the 3D space. However, such dimension extension of the optimization problem is not expected to bring much enhancement of the cost function due to relative small value ranges of additional design variables which are given by construction constraints.

Having computed the design parameters, the viability of the resulting structure has to be proven. The specialty of using parallel mechanism to construct an exoskeleton is that a relatively large working space is required. For the viability proof, maximal and minimal lengths of the actuators must be computed. For this computation, the inverse kinematic equations are used and the leg lengths variation constraints are verified. Fig. 7 shows the length of all six actuators for sitting down from a standing posture.

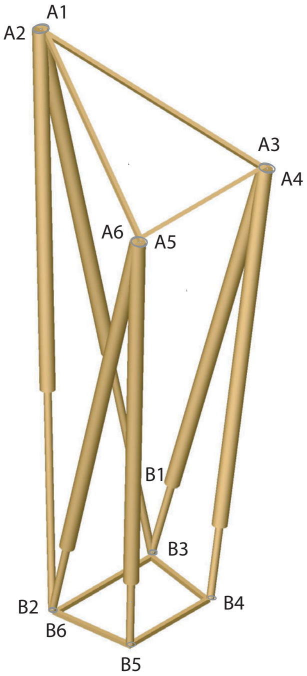

Figure 6: Isometric projection of the hole mechnism

5 Conclusion

A fully parallel mechanism was suggested as a basic construction for an exoskeleton to implement complex movements occurring e.g. in hip joint. An optimal design for the thigh of the exoskeleton was presented. The goal of the optimization was avoidance of architectural singularities in the defined workspace which automatically results in the reduction of the actuator forces as well as increase of the possible velocities and accelerations at the end-effector. The viability of the suggested design was demonstrated.

The further work of the authors in this area is concentrated on the dynamical simulation of the proposed mechanical structure and on the development of its control.

The entire exercise can be repeated for other parts of the exoskeleton, using suitably designed parallel mechanism elements, to achieve motions required at other joints.

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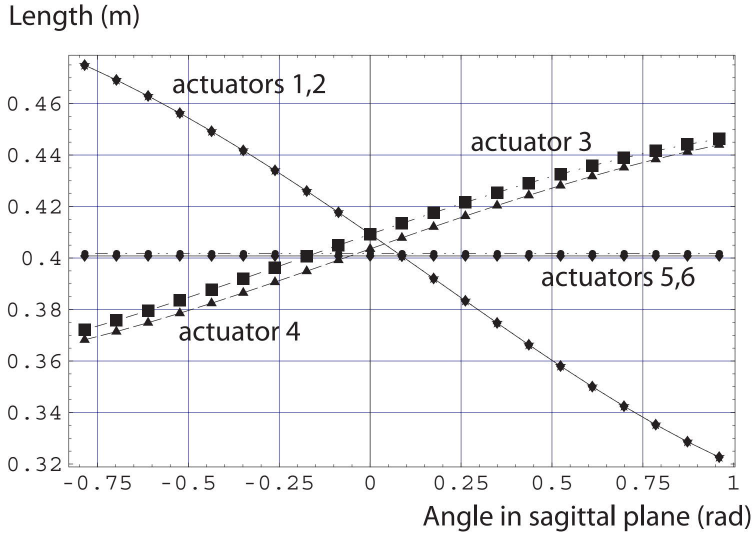

Figure 7: Changing the lengths of the actuators during the sitting down or standing up

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