A Systematic Analysis of the Knee Support Exoskeleton Based on Multibody Dynamics Toward Personalization with 3D printed Spring-Damper Components

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Abstract

Exoskeleton-type assistive devices have been studied a long time focusing on the universal design and a simplification for mass production, and recently the concept is extended to the personalization according to the advancement of 3D printing, which allows to embed spring-damper systems in the form of compliant mechanisms. Therefore, a sophisticated kinematic and kinetic analysis is highly important for the realization of integrative systems and theories of multibody dynamics enhance the capability to find best parameters that are suitable for target body requirements. We analyzed a knee support exoskeleton in the form of the linkage system as the rigid-body dynamics and estimated necessary spring-damper components in the system to reduce burden on joint motions, especially persons with joint dysfunctions.

Keywords: Knee support, exoskeleton-type assistive device, multibody dynamics (MBD), joint dysfunction.

1. Introduction

The knee joint is a vulnerable and important joint for walking and then knee injuries have a serious impact on normal living ability of patients [1]. Therefore, understanding of the biomechanics of a normal and damaged knee joint is crucial for providing an actual support and it is beneficial for designing knee assistive devices with an appropriate optimization of parameters of the device to fit for successive rehabilitation program. Traditionally, exoskeleton-type assistive devices have been provided for the patients with motor disorders especially after neurological injuries and those devices have made rapid strides in recent years by integrating motorized parts and spring-damper mechanisms [2][3]. For example, assistive strategies were modeled with a rotational actuator, a simple pendulum model, and a damped pendulum model, which enhance abilities for normal and fast gaits [2][4]. Indeed, those require a dynamic adaptation to motion kinetics depending on the walking environment and model-based analyses highly important for evaluating of the joint torque and knee stiffness [4][5], which extend capabilities of exoskeleton-type assistive devices [6][7][8].

In this study, we introduced a systematic mathematical analysis based on the multibody dynamics [9][10][11][12][13] for motion kinetics occurring the knee joint support. In the realization of the systematic analysis, necessary joint torque and knee stiffness can be estimated clearly and it helps to design supportive mechanisms to provide a load reduction of the joint in the rehabilitation stage. The model-based kinetic and dynamic analysis were designed for detail investigations on exact timing and position for an effective support and it allows to know necessary improvements of the support devices.

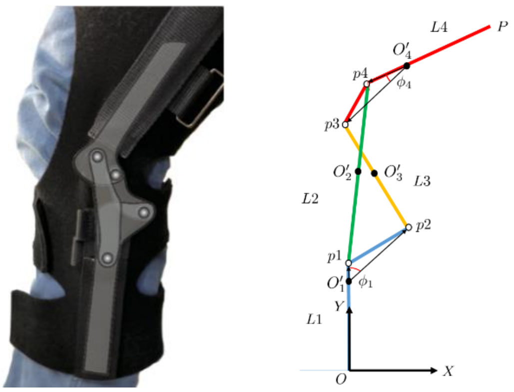
2. Methodology

2.1. Knee link model

The expert orthosis design provided by welfare device companies suggest that the human knee joint cannot be simply replaced by the single rotational joint, but it can be modeled as a combination of rotational joints and translational movements [14] as shown in Fig. 1 (a). In consideration of the knee analysis model, it is possible to analyze the knee movement and trajectory by using a simplified linkage mechanism as illustrated in Fig. 1 (b).

Table 1: Link model specifications

Parameter	Sides	Length [mm]
l_{10}	$O_1'\ O$	40
l_{11}	$O_1'\ p1$	1
l_{12}	$O_1'\ p2$	47
l_{21}, l_{22}	$O_2'\ p1, O_2'\ p4$	50
l_{31}, l_{32}	$O_3'\ p2, O_3'\ p3$	33
l_{40}	$O_4'\ P$	60
l_{41}	$O_4'\ p3$	100
l_{42}	$O_4'\ p4$	60



(a) (b)

Fig. 1. Rigid link model which reproduces knee mechanism and movement (a) and a simplified linkage mechanism in the rigid orthosis.

2.2. *MBD for knee link model*

In order to obtain the motion of each link and the change in the angle of each joint when a constant angular velocity is given to the joint p3 (Fig. 1 (b)) as the knee joint extension, multibody dynamics (MBD) [9][10][11] [12][13] was introduced. MBD is capable of numerical analysis that handles the motion and force of the multisystem simultaneously by describing the motion of a mechanism or structural system composed of various parts. A set of differential equations in the matrix represents constraints, kinematics and kinetics of the system and the numerical integration in the computer experiment provides the actual solution. Thus, in the MBD analysis, the differential algebraic equation is derived from the generalized coordinates. In forward dynamics analysis by MBD, a differential algebraic equation as Eq. (1) is necessary for the formulation of the target system, which provides individual positions of bodies of the system and velocities, acceleration and other factors for kinematic and kinetic analyses can be obtained.

$$\begin{bmatrix} M & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} Q^A \\ \gamma \end{bmatrix} \quad (1)$$

Table 2. The planning and control components.

M	Mass matrix
Φ_q	Jacobian matrix differentiated from constraint equation in generalized coordinates
$\ddot{q}$	Generalized acceleration matrix
λ	Lagrange multiplier
Q^A	Generalized force
γ	Acceleration equation

The mass-center coordinates and the angle of each link are set as shown in Fig. 2. The generalized coordinate matrix and the generalized velocity matrix for each mass center are expressed as follows.

$$q_i = [x_i \quad y_i \quad \theta_i]^T$$
$$\dot{q}_i = [\dot{x}_i \quad \dot{y}_i \quad \dot{\theta}_i]^T$$

The whole generalized coordinate matrix and the generalized velocity matrix are expressed as follows.

$$\mathrm{q} = [q_1 \quad q_2 \quad q_3 \quad q_4]^T$$
$$\dot{q} = [\dot{q}_1 \quad \dot{q}_2 \quad \dot{q}_3 \quad \dot{q}_4]^T$$

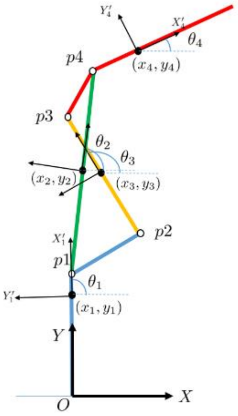


Fig. 2. The definition of generalized coordinates.

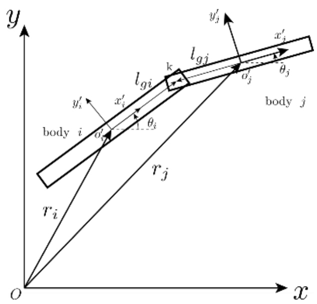


Fig. 3. The definition of kinematic constrains of rotary joint.

The kinematic constrains of rotary joint is defined as shown in Fig. 3 and expressed as follows.

$$\Phi_k^{R(i,j)} = \left(\begin{bmatrix} x_j \\ y_j \end{bmatrix} + A_j \begin{bmatrix} -l_{gj} \\ 0 \end{bmatrix}\right) - \left(\begin{bmatrix} x_i \\ y_i \end{bmatrix} + A_i \begin{bmatrix} l_{gi} \\ 0 \end{bmatrix}\right) = \begin{bmatrix} x_j - x_i - l_{gj}\cos\theta_j - l_{gi}\cos\theta_i \\ y_j - y_i - l_{gj}\sin\theta_j - l_{gi}\sin\theta_i \end{bmatrix} = 0$$

The kinematic constraints of rotary joints in rigid knee link are expressed as follows.

$$\Phi^K = \begin{bmatrix} \Phi_{p1}^K \\ \Phi_{p2}^K \\ \Phi_{p3}^K \\ \Phi_{p4}^K \end{bmatrix} = \begin{bmatrix} \left(\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} + A_2 \begin{bmatrix} -l_{21} \\ 0 \end{bmatrix}\right) - \left(\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} + A_1 \begin{bmatrix} l_{12} \\ 0 \end{bmatrix}\right) \\ \left(\begin{bmatrix} x_3 \\ y_3 \end{bmatrix} + A_3 \begin{bmatrix} -l_{31} \\ 0 \end{bmatrix}\right) - \left(\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} + A_1 \begin{bmatrix} l_{41}\cos\phi_1 \\ -l_{41}\sin\phi_1 \end{bmatrix}\right) \\ \left(\begin{bmatrix} x_4 \\ y_4 \end{bmatrix} + A_4 \begin{bmatrix} -l_{41}\cos\phi_4 \\ -l_{41}\sin\phi_4 \end{bmatrix}\right) - \left(\begin{bmatrix} x_3 \\ y_3 \end{bmatrix} + A_3 \begin{bmatrix} l_{32} \\ 0 \end{bmatrix}\right) \\ \left(\begin{bmatrix} x_4 \\ y_4 \end{bmatrix} + A_4 \begin{bmatrix} -l_{42} \\ 0 \end{bmatrix}\right) - \left(\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} + A_2 \begin{bmatrix} l_{22} \\ 0 \end{bmatrix}\right) \end{bmatrix} = 0$$

The link 1 set vertically, and then x_1, y_1, θ_1 is provided as follows according to the absolute constraints.

$$\Phi^A = \begin{bmatrix} x_1 \\ y_1 - L1 \\ \theta_1 - \dfrac{\pi}{2} \end{bmatrix} = 0.$$

The driving constraints when a constant angular velocity is given to the joint p3 is expressed as follows.

$$\Phi^D = \theta_4 - \omega t = 0$$

The kinematic, and absolute and driving constraints are combined in the matrix as follows.

$$\Phi = \begin{bmatrix} \Phi^K \\ \Phi^A \\ \Phi^D \end{bmatrix} = 0$$

Finally, the Jacobian matrix is follow.

$$\Phi_q = \begin{bmatrix}
-1 & 0 & l_{11}\sin\theta_1 & 1 & 0 & l_{21}\sin\theta_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & l_{11}\cos\theta_1 & 0 & 1 & l_{21}\cos\theta_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & l_{12}\sin\phi_1-\theta_1 & 0 & 0 & 0 & 1 & 0 & l_{31}\sin\theta_3 & 0 & 0 & 0 \\
0 & -1 & l_{12}\cos\phi_1-\theta_1 & 0 & 0 & 0 & 0 & 1 & l_{31}\cos\theta_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & l_{32}\sin\theta_3 & 1 & 0 & l_{41}\sin\phi_4+\theta_4 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & l_{32}\cos\theta_3 & 0 & 1 & l_{41}\cos\phi_4+\theta_4 \\
0 & 0 & 0 & -1 & 0 & l_{21}\sin\theta_2 & 0 & 0 & 0 & 1 & 0 & -l_{42}\cos\theta_4 \\
0 & 0 & 0 & 0 & -1 & l_{21}\cos\theta_2 & 0 & 0 & 0 & 0 & 1 & -l_{42}\sin\theta_4 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix}$$

In the MBD analysis, the resultant Jacobian matrix is applied to the differential algebraic equation Eq. (1) and then a generalized acceleration matrix is numerically calculated as a numerical solution.

3. Results

The MBD differential algebraic equation of motion for the knee rigid link model was successfully solved with the generalized acceleration matrix, and the angle and angular velocity were obtained by using the numerical integration of the Runge-Kutta Gill's method [15].

In computer experiments, MATLAB was used.

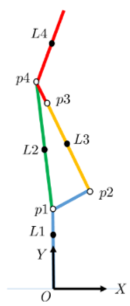


Fig. 4. The singular point posture of the knee model.

3.1. *The movement of the knee link model*

In the process of the knee joint extension, the angle, angular velocity and angular acceleration of each link were analyzed in the condition that a constant angular velocity is given to θ_3. Interestingly, this knee link model has a limitation of the range of the joint extension to prevent the breakage of the knee joint, which was derived in the form of a singular posture (Fig. 4) just before line link L3 and L4 is getting to be on the same straight line. It implies that the rotation of the link is locked in this specific angle. It indicates that the linkage model finely represents the freedom of the knee joint and its limitation. Therefore, the result clarified the importance of the analysis of the singular posture based on MBD [16].

3.2. *The results of the dynamic analysis*

The kinetic analysis was successfully obtained as shown in Fig. 5. The temporal evolution of angle of individual joints as p1, p2, p3 and p4 were denoted by blue, red, yellow and green lines respectively.

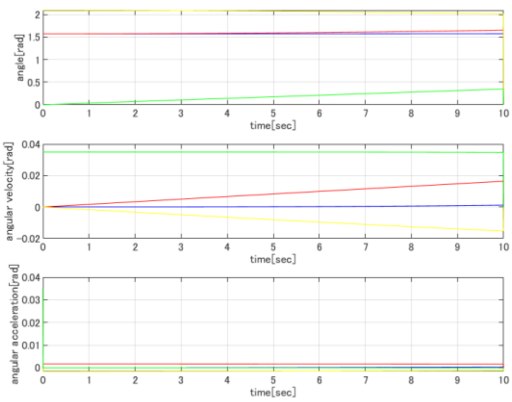


Fig. 5. The result of kinematic analysis ($\theta_4 = 0° \sim 20°$).

4. Conclusion

According to the MBD analysis for the knee joint linkage model, necessary factors in kinematics and kinetics were successfully obtained and the limitation of the movement was clarified in the form of the singular posture. This result demonstrated that MBD-based analysis is beneficial for the reverse engineering to complement the ideal load reduction at a specific posture to avoid risks of the joint movement. In the further analysis, the comparison with/without an additional spring-damper system to prevent the singular posture can be discussed.

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