A Gait Analysis with Multibody Dynamics Toward Energy-Efficient Active Knee Prostheses

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Abstract

In general, prosthetic knee users have a large stress in the locomotion due to less smoothness and unnecessary energy consumption. In the passive prosthesis, it is difficult to regulate the stiffness depending on the ground contact force. In consideration of designs for such an adaptivity to improve passive systems, we propose an artificial knee kinematics design to absorb the redundant contact force for the smooth and stable walking and explore necessary constraints for the proposed mechanics to be able to have multi-functions not only for walking but also knee flexion accumulating the power for jumping. In the analysis, we used Multibody Dynamics (MBD) to investigate. This result will contribute to design an integrated dynamic model by incorporating a flexible body and ground contact forces in various purposes.

Keywords: Multibody dynamics (MBD), Contact force model, Prosthetic knee, Ordinary differential equation

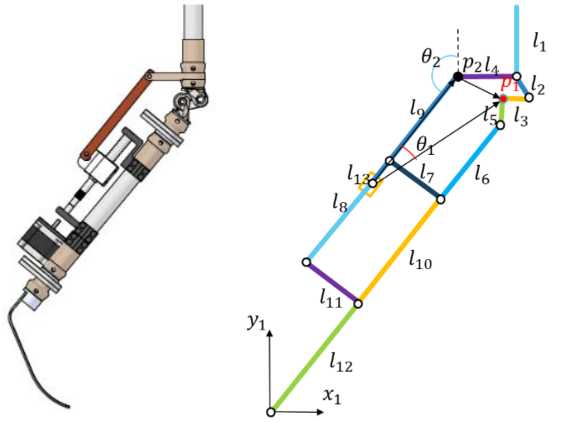
1. Introduction

Knee prosthesis users have high energy expenditure and motion load due to their different gait characteristics [1]. Therefore, developing knee prosthesis designs is an important research area, especially for lower limb amputation patients, to improve their mobility and quality of life. The knee joint is crucial in improving biomechanical efficiency and is a key component in supporting and transmitting load during walking, running, and stair climbing [2], [3]. However, prosthetic users face difficulties in replicating the motion of a real human knee, which leads to increased physical stress and energy consumption, especially during high-impact activities. Active prostheses use actuators and control systems to support joint movement and improve gait kinematics, but they suffer from weight gain, metabolic cost, and energy expenditure [4]. Passive prostheses cannot actively generate knee joint rotation, so above-knee amputees have more difficulty climbing stairs and ramps, and transitioning between sitting and standing, than non-amputees [5]. Therefore, there is a need to improve prosthetic technology to meet the unmet needs of people with above-knee amputees. To consider an adaptive model to improve the passive system, we propose a kinematic design of an artificial knee that incorporates additional hardware to support a smooth and stable gait and explore the constraints required to enable the proposed mechanism to perform multiple functions. Not only walking, but also knee flexion accumulates the force of jumping [6], [7]. In the analysis, we conducted research using Multibody Dynamics (MBD) [8], [9]. This result contributes to the development of a unified dynamic model by characterizing the rigid body interaction forces as a function of the motion constraint conditions [10]. In addition, modeling contact forces allows for detailed gait analysis by simulating the interactions between body parts and motion. By integrating these elements into a multibody dynamics (MBD) framework, we develop an analytical system for evaluating human biomechanics. The proposed approach contributes to the development of energy-efficient prosthetic devices designed to support natural, dynamic movement, increase user comfort and function, and address the limitations of current technologies.

2. Methodology

2.1. Knee prosthesis model

This paper proposes a kinematic design method of passive system prosthetic knee that adds a limited to the new knee joint to lock the knee joint for stable walking. The dynamic model kinematic mechanism proposal can be analyzed. However, it can be modeled by transferring the motion by making one more connecting mechanism as shown in Fig. 1. Considering the knee joint analysis model, the Prosthetic knee motion and trajectory can be analyzed using a simplified connecting mechanism as shown in Fig. 1 (b).



(a) (b)

Fig. 1. Prosthetic knee modified CAD model (a) and Prosthetic knee simplified joint mechanism (b).

2.2. Multibody system formulation for Knee link model

The knee joint angle is a critical factor in human walking, influencing motion and stability. To examine the relationship between the knee joint angle Fig. 1 (b) and the resulting joint motion and angular changes, multibody dynamics (MBD) [9], [10], [11], [12] was employed. Our approach is based on the previous work of Batbaatar & Wagatsuma (2021) [6], [10], In which authors used MBD to study the ground reaction forces during walking and running in a horse leg model. Inspired from their methodology, we analyzed the human walking process and implemented appropriate constraints in our system to identify the key factors affecting to the movement. For our prosthetic knee design, these constraints were adjusted to maintain mechanical stability while operating smoothly in a variety of activities. The mathematical model of the artificial knee joint mechanism is described using multibody dynamics (MBD), and the position and orientation of each body in the leg mechanism can be written as Eq.1 which is a 39-element vector called a generalized coordinate q.

$$q = [q_1^T, q_2^T, q_3^T, \dots, q_{13}^T]^T \qquad (1)$$

The vector of q contains $q = R_N \times 3$ elements which are 13 rigid links and their center of position x_i, y_i and orientation ϕ_i are obtained in the generalized coordinates in the present analysis. Where the first 38 elements of the column matrix of kinematic constraint equation $\Phi^{K}(q)$ are derived from the absolute constraints between body and fixed ground node. The last elements in $\Phi_{(q,t)}$ defines the driver constraint of the proposed leg mechanism. Considering the initial configuration (Linear actuator), the driver constraint equation can be written as Eq.2.

$$\Phi^{D}_{(q,t)} = \begin{bmatrix} x_{13} \\ y_{13} \end{bmatrix} - \left(\begin{bmatrix} x_8 \\ y_8 \end{bmatrix} + A_8 \begin{bmatrix} -\frac{l_8}{4} cos(\omega t) \\ 0 \end{bmatrix} \right) \qquad (2)$$

The differential-algebraic equations of motion for the knee stiffener model were effectively solved using the generalized acceleration matrix, allowing for the accurate computation of joint angles and angular velocities. These results were obtained through numerical integration employing the Runge-Kutta Gill's method [13].

The partial derivative of kinematic constraint equation with respect to the generalized absolute Cartesian coordinates q is Jacobian matrix Φ_q is obtained as Eq.3.

$$\Phi_q = \left[\frac{\partial \Phi(q,t)}{\partial q} \right]_{39 \times 39} \qquad (3)$$

Where it allows us to investigate placement, velocity and acceleration analyses kinematically. The forward dynamics analysis introduces the mass matrix $M = (39 \times 39)$ as Eq.4, and the generalized external force vector $h^{(a)} = (39 \times 1)$, as Eq.5.

$$M = diag(M_1, M_2, \dots, M_{13})$$
$$\{M_i = [m_i, m_i, J_i]^T | i = 1,2,\dots,13\} \qquad (4)$$

$$h^{(a)} = \left[h_1^{(a)^T}, h_2^{(a)^T}, \dots, h_{13}^{(a)^T} \right]^T$$
$$\{h_i^{(a)} = [0, -m_i g, 0]^T | i = 1,2,\dots,13\} \qquad (5)$$

Where m_i is the mass of rigid link to point, $J_i = 2l_i/3$ is the polar moment of inertia of rigid link to point i, and g is the gravitational acceleration. The equation motion of the system for the computer system analysis can be is expressed in general matrix form as Eq.6.

$$\begin{bmatrix} M & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} Q^A \\ \gamma \end{bmatrix} \qquad (6)$$

This system of the equation can be solved for acceleration $\ddot{q}$, and Lagrange multipliers λ. In order to obtain coordinates q and velocities $\dot{q}$, acceleration is integrated at instant of time $t = t + \Delta t$. For the forward dynamic analysis, to ensure the numerical accuracy in the general solution of motion equation, constraint stabilization Baumgarte method is used with the following parameters α and β. In the forward dynamic analysis, new coordinates and velocities require two arrays for $\dot{q}$ and $\ddot{q}$ for the time step $t + \Delta t$ as Eq.7.

$$u = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}, \quad \dot{u} = \begin{bmatrix} \dot{q} \\ \ddot{q} \end{bmatrix}, \quad \dot{u} \xrightarrow{yields} u(t + \Delta t), \qquad (7)$$

At the starting point of the numerical simulation, initial configurations of target mechanisms are given according to the primary operation in forward dynamics analysis.

3. Results & Discussion

Numerical analysis was performed using kinematic and dynamic simulations based on the above MBD formulation. This constraint allowed us to calculate the foot motion and visualize the time evolution of the ground reaction force within the knee mechanism.
All simulations and computational experiments were performed using MATLAB, which is perfectly suited for implementing the MBD framework and analyzing the dynamic behavior of the system.

Table 1. Parameters used in numerical simulations.

Kinematic/Dynamic analysis		
Gravitational acceleration [m/s^2]	g	9.81
The velocity of the driving crank [rad/s]	ω	$\pi/3$
Total simulation time [s]	t	$0 \le t \le 12$
Baumgarte parameter	α	0.8
Baumgarte parameter	β	35
Time step [s]	dt	1.0×10^{-3}

Summarizes the numerical simulation parameters used to analyze the contact forces in the foot mechanism (Table 1). The MBD differential-algebraic equations of motion for the knee rigid-joint model were successfully solved using the generalized acceleration matrix, and the angles and angular velocities were calculated by numerical integration using the Runge-Kutta Gill's method [13].

Computer experiments were performed using the MATLAB program.

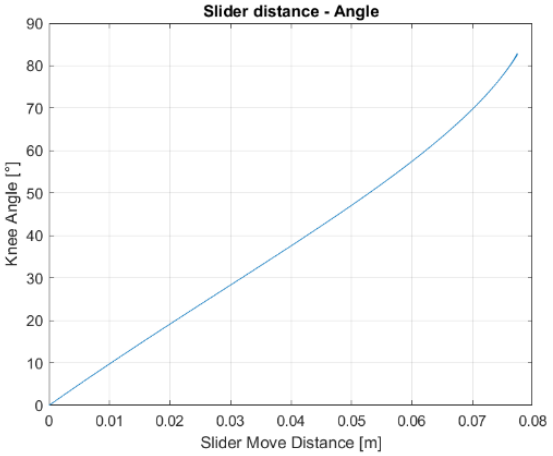


Fig. 2. Slider distance Knee Angle

The plot in Fig. 2 illustrates the relationship between the slider's displacement and the knee angle expressed in degrees. This relationship is nonlinear, indicating that even small changes in the sliding distance can lead to changes in the knee angle. This diagram highlights the sensitivity of the knee joint to sliding motion. This relationship is essential for applications such as robotics or biomechanical simulations, where precise control of the joint angle is important.

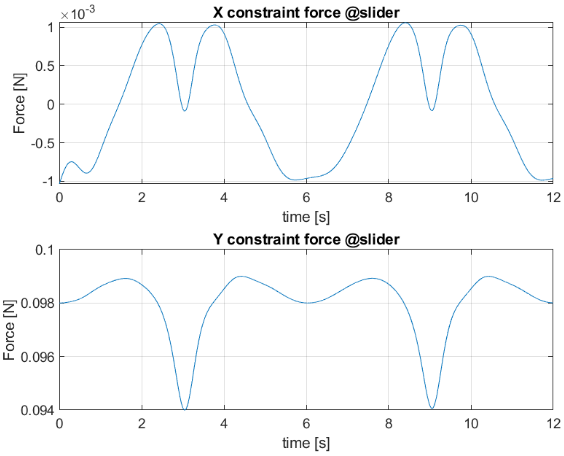


Fig. 3. X and Y Constraint Forces at the Slider

Fig.3 shows the forces (X and Y) acting on the slider over time due to mechanical restraints. This motion is clearly oscillating with the slider's cycle of motion.

This oscillation represents the dynamic interaction between the slider and the other components of the system.

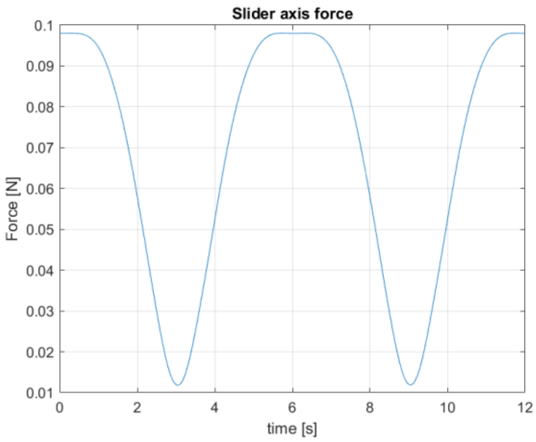


Fig. 4. Slider Axis Force Over Time

Fig.4 shows the net force along the axis of motion of the slider, which is the sum of the forces in the X and Y directions in the local coordinate system of the slider. The force varies over time in accordance with the cycle of the slider's motion. Analyzing the net force along the axis of the slider is essential to ensure that the system operates within safe force limits. It also provides insight into the energy transfer and efficiency of the mechanism. The relatively small forces acting on the slider and associated components, as shown in Fig. 1 indicate that the system is designed for precise use beyond the mass-weight relationship. Also, the strong dependence of the knee angle and the slider displacement, shown in Fig. 2 indicates the need for precise control of the slider motion. The dynamic forces acting on the various parts of the system demonstrate the complexity of the interactions between the components, requiring careful calculations for robust constraints and load analysis.

4. Conclusion

The critical kinematic and kinetic factors were successfully identified using MBD (Multibody Dynamics) analysis for the knee joint model. In addition, the motion constraints of the system were clarified by identifying the motion constraints, especially the critical positions that limit the motion. The high sensitivity of the knee joint behavior affects the motion of the slider. This combined analysis of MBD and MATLAB simulations provides valuable insights for the design and optimization of mechanical systems in robotics, biomechanics, and other fields where precise motion control and load management are required. In the future this result will contribute to design an integrated dynamic model by incorporating a flexible body and ground contact forces in various purposes.

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