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DYNAMIC CHARACTERISTICS ANALYSIS AND EXPERIMENTAL VALIDATION OF STAIR GAIT FOR LOWER LIMB EXOSKELETON ROBOT

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Abstract - This paper delves into the kinematic and dynamic characteristics of human lower limb movement during stair climbing, leveraging the gait characteristics of exoskeleton robots and a mathematical model tailored for stair-climbing gait. Through a combination of theoretical derivation, simulation, and experimental validation, we comprehensively analyzed these characteristics. The experimental results unveil periodic displacement changes in the hip, knee, and ankle joints. Notably, these joints exhibit significant horizontal displacements and a continuous upward trend in vertical displacements, while lateral sway remains minimal. Furthermore, the joints demonstrate substantial velocities and accelerations, with angle variations falling within the normal range of human mobility. An analysis of ground reaction forces reveals contrasting trends in force distribution between the left and right feet, with both feet experiencing considerable maximum forces and moments. These findings not only provide detailed data support for understanding the intricate movement patterns during stair climbing but also offer invaluable references for further research and practical applications in related fields.

Keywords: Lower limb rehabilitation robot; motion characteristics; Motion Capture; Experimental Validation.

1. Introduction

Lower limb exoskeleton robots, as intelligent devices that assist lower limb movement, have broad application prospects in fields such as rehabilitation medicine, disability assistance, and industrial augmentation[1-2]. Stair climbing, involving factors like center of gravity shifts, joint angle variations, and gait coordination, serves as a critical metric for evaluating the practical performance and stability of exoskeleton robots. However, the dynamic characteristics of stair ascent are highly complex, imposing greater demands on the mechanical structure and control systems of exoskeletons[3-5].

Research on stair gait for lower limb exoskeleton robots began earlier abroad, focusing on motion control algorithms and ergonomic analysis. Teams in the United States and Japan, through dynamic modeling and biomechanical experiments, proposed efficient joint trajectory planning and gait generation methods, significantly improving the smoothness and stability of robot movements[6-7]. European teams developed real-time collaborative control technologies based on electromyographic signals and plantar pressure feedback, enhancing the adaptability and user experience of exoskeletons[8].In China, research is based on technology importation and independent innovation, achieving significant progress in lightweight design, compliant control, and multi-modal sensing technologies[9-10]. Teams from Beijing University of Technology and The Affiliated Hospital of Qingdao University proposed gait recognition and motion prediction methods based on deep learning, greatly enhancing intelligence levels[11]. However, challenges remain in adaptability testing for complex

https://doi.org/10.17683/ijomam/issue19

environments and large-scale clinical validation[12-15]. Strengthening experimental platform development and interdisciplinary collaboration is crucial to optimize dynamic characteristic analysis, joint design, and control strategies, thereby improving adaptability in complex environments and providing theoretical support for practical applications[16-18].

2. Structural Design of a Wearable Exoskeleton Robot for Lower Limb Rehabilitation

The overall model of the lower limb exoskeleton robot was developed using SolidWorks software. The model includes adjustable structures such as the waist component, joint module fixtures, thigh component, leg straps, calf component, and foot component[19-21]. The overall design is shown in Figure 1.

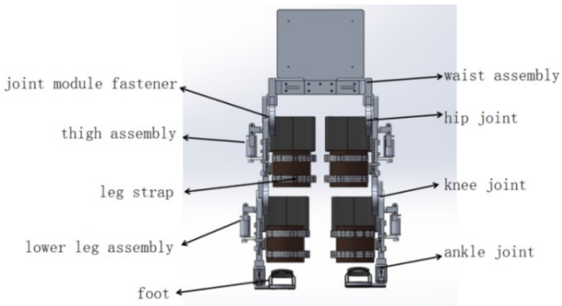


Figure 1: Overall structure

3. Kinematic Analysis of Stair-Climbing Posture

The inverse kinematic analysis of the stair-climbing posture is similar to the forward kinematic analysis of walking posture[22-24]. This section focuses on the inverse kinematics of stair-climbing. It is assumed that during the stair-climbing process, the upper body remains perpendicular to the ground, the hip joint and both feet remain parallel to the ground, and the free axis of the ankle joint intersects with the joint center. The stair-climbing model of the lower limb exoskeleton is shown in Figure 2.

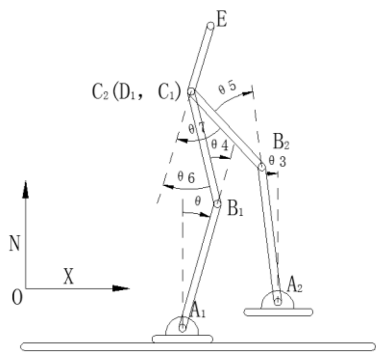


Figure 2: Stair-Climbing Model of the Lower Limb Exoskeleton

When the right leg serves as the support and the left leg is in a stair-climbing posture, the lengths of the lower leg and thigh are defined as L1and L2, defined as point H,and the position of the ankle joint is defined as point A.The position expression for the hip joint H can be derived as follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} L_1 \sin\theta_2 + L_2 \sin(\theta_2 - \theta_4) \\ (L_1 \cos\theta_2 + L_2 \cos(\theta_2 - \theta_4))\sin\theta_0 \\ (L_1 \cos\theta_2 + L_2 \cos(\theta_2 - \theta_4))\cos\theta_0 \end{bmatrix} \tag{1}$$

The angle θ_1 at the ankle joint can be further calculated based on the position of the hip joint.

$$\theta_1 = \arctan\frac{y_{C_1}}{z_{C_1}} = \arctan\frac{(L_1 \cos\theta_2 + L_2 \cos(\theta_2 - \theta_4))\sin\theta_1}{(L_1 \cos\theta_2 + L_2 \cos(\theta_2 - \theta_4))\cos\theta_1} \tag{2}$$

The calculation of the hip joint angle θ_2 and knee joint angle θ_4 can be transformed into solving the kinematics of a two-link mechanism. In a $X-Z$ plane, a polar coordinate system can be established to represent the positions. By applying the law of cosines (r,ϕ), the hip joint angle and knee joint angle can be determined as follows:

$$\theta_2 = \arccos\left(\frac{r^2 + L_1^2 - L_2^2}{2L_1 r}\right) \tag{3}$$

$$\theta_3 = \arctan\left(z_{C_1}, x_{C_1}\right) \tag{4}$$

Constraints and kinematic pairs were added to the lower limb exoskeleton model based on the positional and motion relationships of various body parts during stair climbing[25-27], as shown in Figure 3. Figures 4 to 9 illustrate the stair-climbing motion curves for the hip, knee, and ankle joints of both legs, showing the variation trends in position, velocity, and acceleration for each joint.

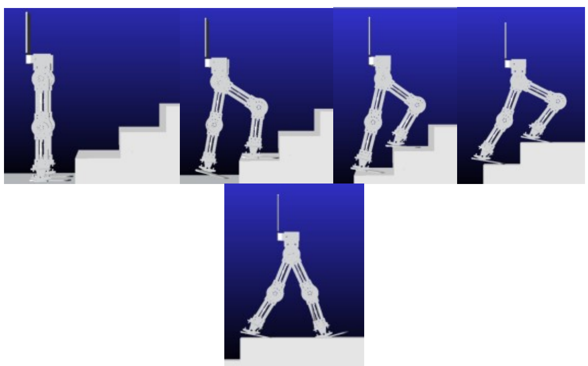


Figure 3: Schematic Diagram of Human Stair-Climbing Motion Simulation

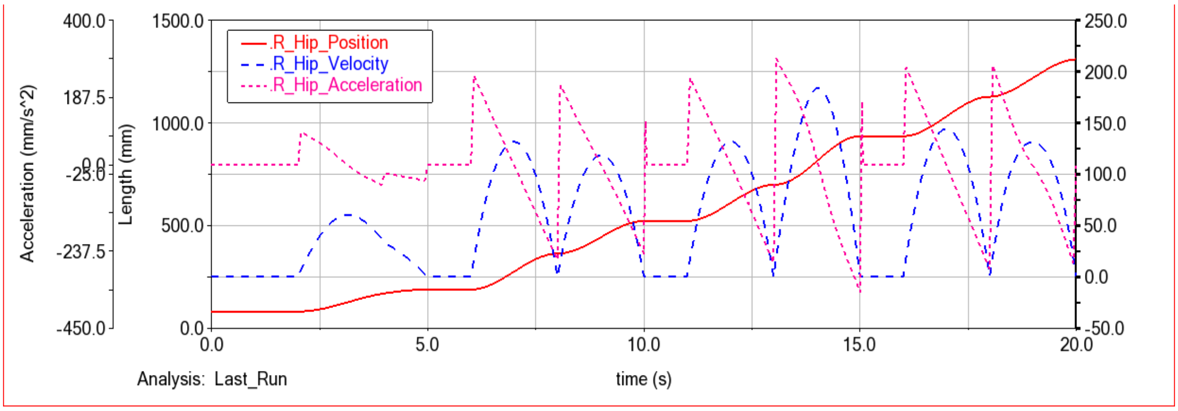


Figure 4: Right Hip Joint Stair Climbing Kinematics

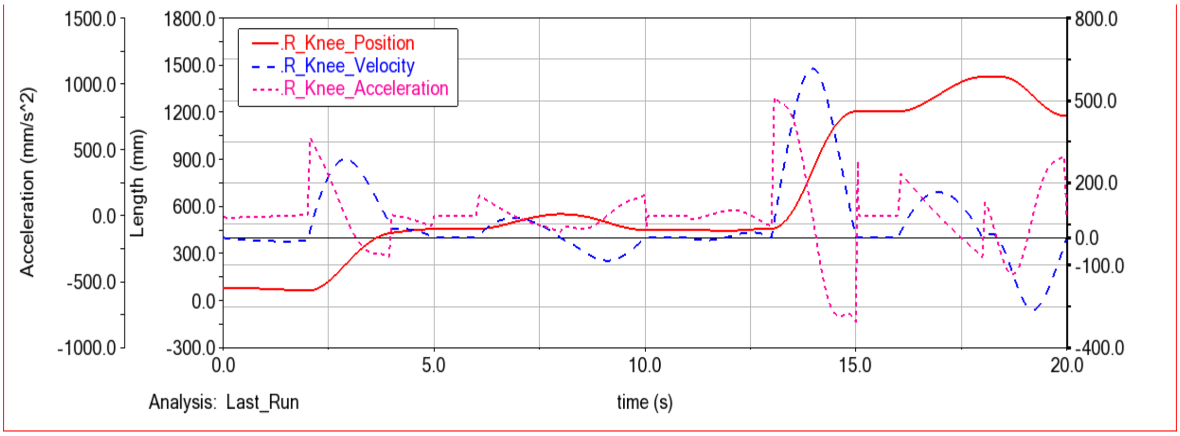


Figure 5: Right Knee Joint Stair Climbing Kinematics

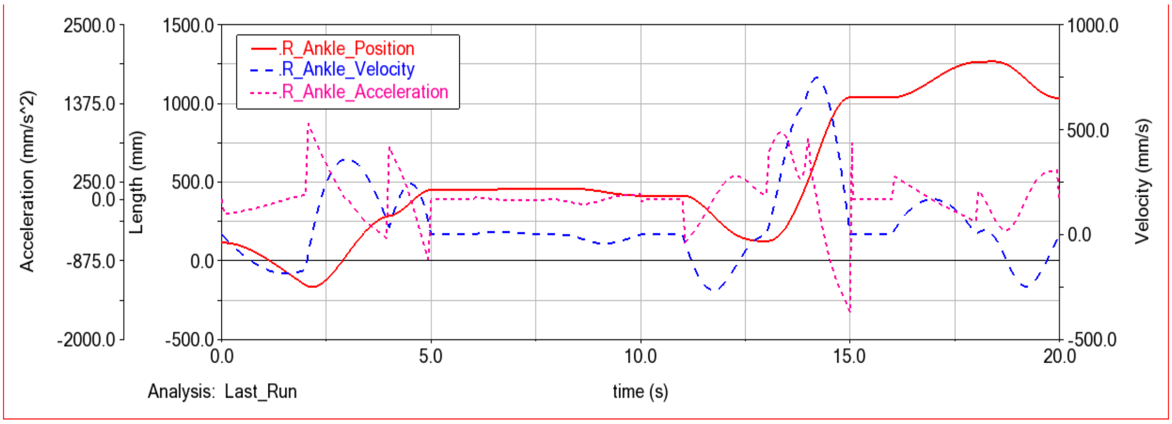


Figure 6: Right Ankle Joint Stair Climbing Kinematics

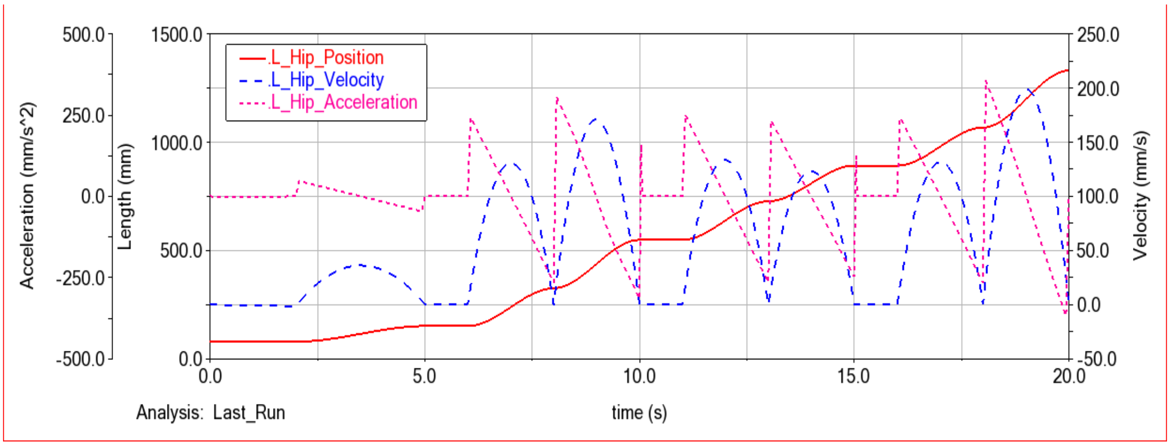


Figure 7: Left Hip Joint Stair Climbing Kinematics

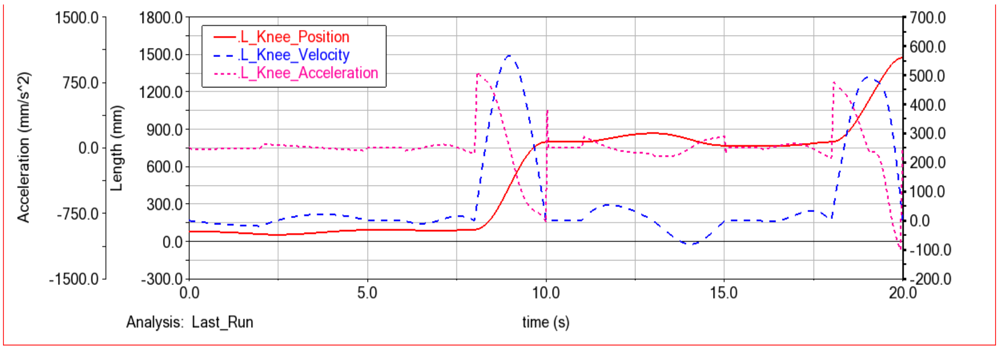


Figure 8: Left Knee Joint Stair Climbing Kinematics

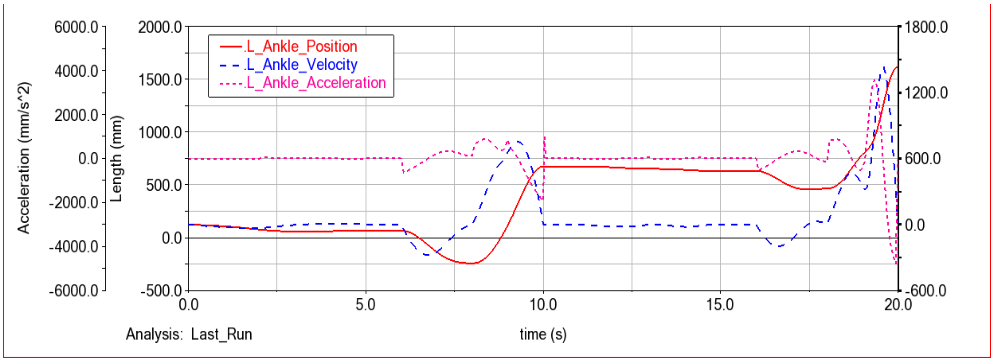


Figure 9: Left Ankle Joint Stair Climbing Kinematics

As can be seen from the figure above, under conditions of slow movement, the kinematic trajectories of the left and right legs are essentially overlapping. During the stair climbing motion, the maximum vertical displacement of the hip joint is 250 mm, the minimum displacement is 80 mm, with a difference of 170 mm. The maximum displacement of the knee joint is 750 mm, the minimum displacement is 375 mm, with a difference of 375 mm. The maximum displacement of the ankle joint is 925 mm, the minimum displacement is 282 mm, with a difference of 643 mm. All these displacements fall within the active range of motion for the hip, knee, and ankle joints in the human lower limb.

4. Stair Climbing Posture Experiment Verification

First, the purpose and procedure of the test are explained. The data collection for this experiment was conducted using the NOKOV Motion Capture System. The experiment is divided into two phases: the stair climbing phase and the stationary phase. It is important to perform the movements slowly to ensure that all the marker points are captured accurately. The initial posture is the standing position, followed by the stair climbing motion. One foot is placed on a force plate, and then the other foot is lifted to step onto the second force plate to complete the stair climbing motion. Both feet are then placed on the final platform. After holding the position for two to three seconds, the experiment is concluded. After each trial, ensure that the subject has sufficient time and space to recover, then repeat the experiment three times. Finally, make sure the subject has adequate time and space for recovery.

Figure 10: Marker Placement Locations for the Stair Climbing Posture Experiment Subjects

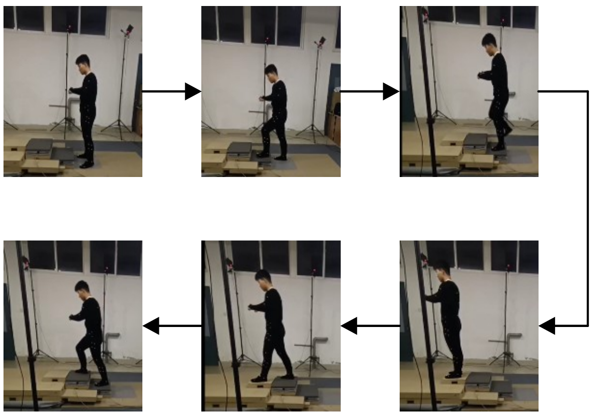
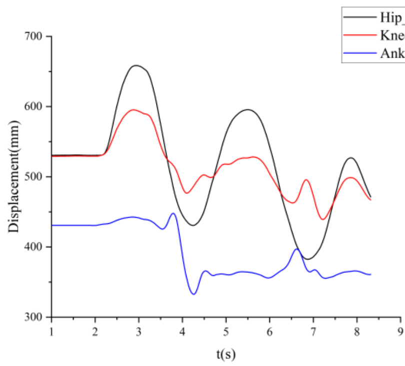


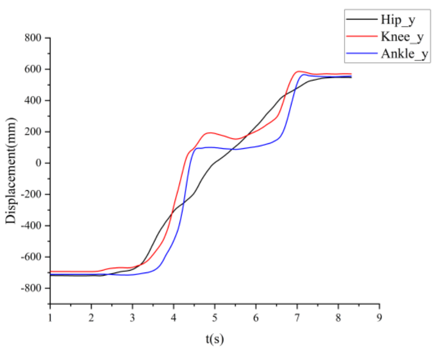
Figure 11: Flowchart of the Stair Climbing Experiment

Figure 12: Human-Robot Collaborative Motion Experiment Diagram

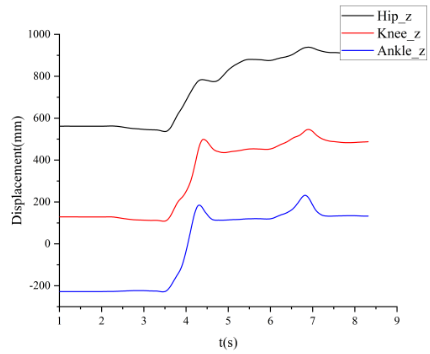
The data of the marker points attached to the subjects during the stair climbing motion experiment were post-processed to obtain the displacement, velocity, acceleration, and angle at the hip, knee, and ankle joints of the lower limb, as well as the variation patterns of the foot sole force and moment, as shown in Figures 13 to 15.



(a) Displacement of each joint in the x-direction

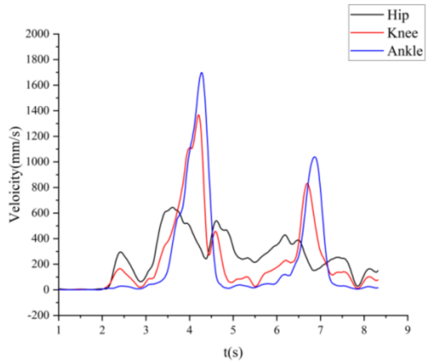


(b) Displacement of each joint in the y-direction

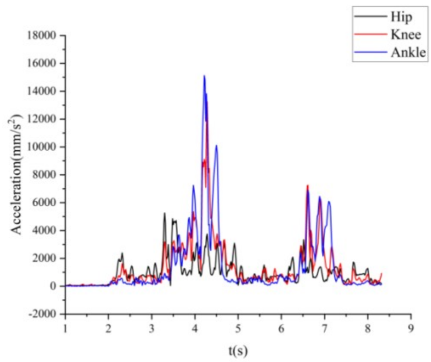


(c) *Displacement of each joint in the z-direction*

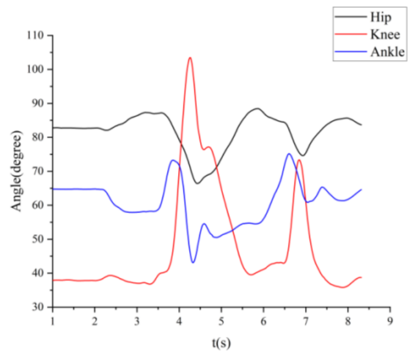
Figure 13: Displacement Variation of Each Joint in the XYZ Directions During Stair Climbing Gait



(a) Velocity Curve of Each Joint

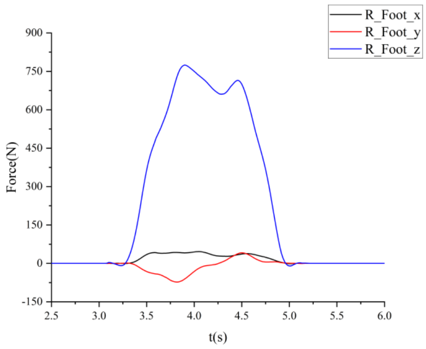


(b) Acceleration Curve of Each Joint

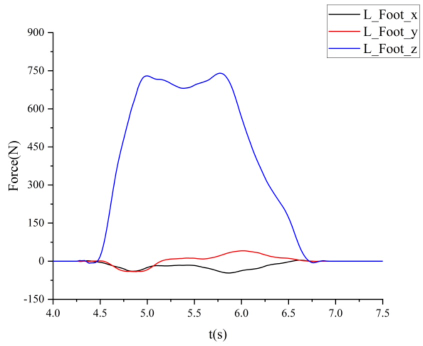


(d) Angle Variation Curve of Each Joint

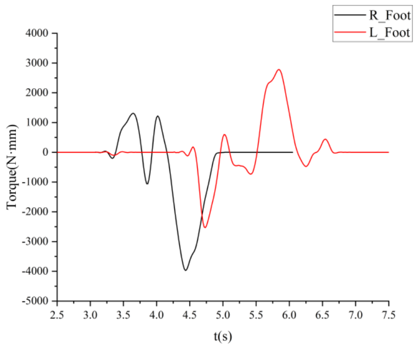
Figure 14: Kinematics and Angle Curves of Each Joint During Stair Climbing Posture



(a) Ground Reaction Force of the Right Foot in EachDirection



(b) Ground Reaction Force of the Left Foot in Each Direction



(c) Moment Curves of the Left and Right Feet

Figure 15: Ground Reaction Force and Moment Curves of the Left and Right Feet During Stair Climbing Posture

From Figure 13, it can be seen that during the stair climbing process, the positions of the hip, knee, and ankle joints in the x-axis direction exhibit periodic changes. When stepping onto a step, the required horizontal displacement for the hip, knee, and ankle joints are 130 mm, 50 mm, and 20 mm, respectively. The y-axis represents the vertical displacement direction of the human body, and the positions of the three joints in the y-axis direction show a gradually increasing trend, indicating that the body is in an upward motion throughout. The z-axis represents the left-right position of the body, and it can be observed that the z-direction position changes of all three joints are minimal, indicating that there is some lateral sway during walking, but the overall direction is forward. It can also be seen that the sequence of position and motion changes from top to bottom is: hip joint, knee joint, ankle joint, which aligns with the position relationships of the lower limb joints and the motion patterns of the human body during stair climbing. This is consistent with the gait experiment requirements and the actual joint motion patterns for stair climbing.

From Figure 14, it can be inferred that during the stair climbing motion, the hip joint has the smallest velocity and acceleration, with a maximum velocity of 0.65 m/s. The knee joint follows, with a maximum velocity of 1.39 m/s. The ankle joint, being the last to move, exhibits the highest velocity and acceleration, with a maximum velocity of 1.71 m/s. In the angle variation curve, the hip joint's range of motion is between 16° and 36°, the knee joint's range of motion is between 22° and 55°, and the ankle joint's range of motion is between 8° and 24°, which is within the typical range of motion for human lower limb joints.

From Figure 15, it can be seen that in the y-axis direction, the ground reaction force acts vertically on the sole of the foot. During one gait cycle of stair climbing, the force variation on the soles of both feet shows an opposite trend. This is because, while the supporting leg provides support, the other side is not engaged in the movement. After the single support phase ends, the double support phase begins, with the new supporting leg starting to bear the body's weight. Subsequently, the reaction force from the previous supporting foot rapidly decreases until it leaves the force platform, at which point the reaction force becomes zero. From the figure, it can be observed that during one gait cycle, the maximum ground reaction force experienced by the right foot sole is 80 N, with a maximum moment of 14.6 Nm. The left foot sole experiences a maximum ground reaction force of 74.2 N, with a maximum moment of 31.5 Nm.

5. Conclusions

The stair climbing experiment and subsequent data analysis reveal key insights into the kinematics and dynamics of human lower limb movement. The results show that during stair climbing, the positions of the hip, knee, and ankle joints exhibit periodic variations, with horizontal displacements of 130 mm, 50 mm, and 20 mm, respectively, when stepping onto a new step. The vertical displacement (y-axis) of the joints continuously increases, indicating an upward motion, while the lateral displacement (z-axis) remains minimal. Furthermore, the velocity and acceleration of the joints show distinct patterns, with the maximum speed of the hip joint reaching 0.65 m/s, the knee joint 1.39 m/s, and the ankle joint 1.71 m/s. The angular ranges of the hip, knee, and ankle joints are 16°–36°, 22°–55°, and 8°–24°, respectively, all within the normal range of human joint mobility.

The ground reaction force data indicate that the force distribution between the two feet during a gait cycle is opposite, with the right foot experiencing a maximum force of 80 N and a maximum moment of 14.6 Nm, and the left foot experiencing a maximum force of 74.2 N and a maximum moment of 31.5 Nm. These findings align with the natural biomechanics of stair climbing and provide valuable data for understanding human motion in this context.

Acknowledgements

This work was supported by Qingdao postdoctoral applied research project (A2020-070), the Natural Science Foundation of Shandong Province (No. ZR2020QE151) and Qingdao Huanghai University doctoral research Fund Project (2020boshi02).

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