DESIGN OF HYBRID MECHANISM OF A LOWER-LIMB KNEE EXOSKELETON FOR TORQUE VARIATION

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Abstract - Research on effective lower-limb exoskeletons for knee joints has become an important requirement while the elderly population is growing at a high rate. To maintain independence and good quality of life, lower-limb mobility exoskeletons are expected to play a vital role for elderly people. It is anticipated that these will help the elderly to continue living in their own homes and carry out their daily activities. This research explores important issues in mechanisms design that need to be addressed to achieve the required functionalities of exoskeletons. This research attempted to combine several mechanisms to develop a novel hybrid mechanism, comprising a four-bar chain for poly-centricity and a scotch yoke for motion reversal. These could be useful as generic components in assistive exoskeletons which are envisaged to be in high demand in the future. The proposed new mechanism is coupled with a continuously variable transmission (CVT) element, which helps adjust the torque as required to perform various motions by different users with varying anthropological dimensions. This means that an exoskeleton that incorporates the new hybrid mechanism can provide the required level of assistance for a range of wearers that have different height, weight, build, and posture. The mathematical and geometrical modeling of the overall human and exoskeleton systems has been carried out using Pro/Engineer and MATLAB/Simulink software. For validation of the results, data of a standard gait cycle has been used to help determine the limits of angle covered by the knee joint during a walking cycle. The limiting value of torque is validated by the data obtained from the work carried out within the AAL Call 4 EXO-LEGS project.

Keywords - CVT-gearbox, Four-bar mechanism, Lower-limb Exoskeletons, Scotch-yoke Mechanism, Wearable Robots.

I. INTRODUCTION

Recent United Nation population studies (www.un.org) estimate significant concerns regarding the growing number of persons above 60 years of age, as shown in Fig. 1. There will be corresponding increased need to address the societal problems faced by elderly people, such as how personal mobility can be provided to elderly people without having to depend on the proportionally decreasing numbers of healthcare workers [2]. Personal mobility is essential for maintaining good health, good quality of life and independence, which make it possible to live in own home for much longer.

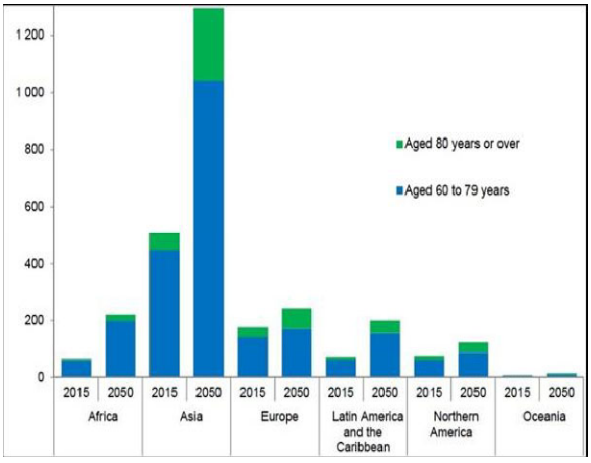


Figure 1: Elderly population: 2015 vs 2050, vertical axis shows population in millions (UN Population website (www.un.org).

Several solutions have been developed and proposed to improve the overall mobility potential of elderly people. These include simple devices such as wheelchairs, supporting sticks and walking frames as well as more sophisticated solutions, such as electric wheelchairs and mobility scooters. Rehabilitation techniques have also been developed to help regain some level of personal mobility by constant application of therapies at regular intervals.

With the advent of technology, a viable solution in the form of exoskeletons [10] has been proposed to assist elderly people in their daily tasks. Exoskeletons are external wearable structures (wearable robots) attached to the wearer's limbs and intended to enhance or replace their movements and so help with tasks such as walking, lifting a load, and more. These should be compliant with user's movements and deliver the needed power necessary to accomplish the desired human motions [7].

Over the last two decades, various wearable robots have been developed such as HAL [11], LOPES [7], ekso [13], ReWalk [18] and others. Most of them use electric actuators, like DC motors, to generate motion at wearer's joints. These motors are coupled with microcontrollers and control systems to alter the speed and torque as necessary. This requires rapid changes in motor power and rotation direction reversal for performing the various motions. This leads to complex control demands due to the wide variation of torque requirements at different joints. The

complexity of varying speed and torque ratios at individual motor level is seen in all exoskeletons that use motors with gearheads and harmonic drives. Harmonic drives are used for large reduction ratios to provide high torques. These devices are efficient but are costly. Moreover, by using gearheads and harmonic drives rather than direct motor drive, the overall drive efficiency is reduced, and the metabolic cost also increases[9]. To address these problems, alternative viable solutions that can provide the required speed/torque requirements at each joint are needed. This can be done by coupling the motor to a mechanism that does this while only requiring constant motor speed. The concept of Continuous Variable Transmission (CVT) used in automotive applications [12] has been suggested, so that motor torques can be varied as needed for performing daily tasks.

CVT mechanisms have not yet been used in assistive exoskeletons although they have been extensively used in automotive applications. With sufficient miniaturization and optimization for wearable exoskeleton applications, CVTs could improve the effectiveness of assistance provided to wearers and thus advance the emerging technology to meet the global need of the ageing society. The aim in this context is to explore the potential of CVTs in assistive exoskeletons. Further, conventional mechanisms, such as scotch yokes [5] and four-bar mechanisms[13] have been investigated in terms of their suitability for use in wearable exoskeletons.

II. TORQUE VARIATION METHODS

A typical exoskeleton consists of several joints driven by actuators like DC motors, springs, pneumatic cylinders, etc. These actuators can provide sufficient and constant speeds for supporting human motions such as walking, running, moving from sitting-to-standing position, moving from standing-to-sitting position, stair climbing, etc. However, the human motions require variable speed/torque characteristics and hence there is a need to employ a speed/torque variation mechanism, which requires a suitable control system.

In exoskeletons with electric motors, gear trains or harmonic drives, the gear ratios must be selected as part of the design. Some powered exoskeletons include a microcontroller. This helps to achieve the required level of torque but at same time leads to greater consumption of power [17]. Other widely used actuators are the hydraulic and pneumatic actuators. The hydraulic or pneumatic systems consists of a fluid pump for power generation, fluid lines for fluid transmission, valves, and flow controllers to control the flow direction and flow rate. All these together become very bulky and heavy for an elderly person to carry. These issues, relevant to exoskeletons for elderly, are briefly listed in Fig. 2 and outlines their limitations for use as torque variation devices in exoskeletons for elderly.

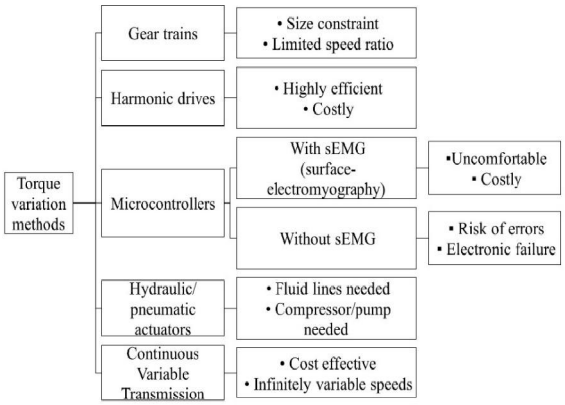


Figure 2: Torque Variation Methods.

III. HYBRID MECHANISM

This part explains how CVT mechanisms can be fitted into assistive exoskeleton for providing required speed/torque parameters in required directions to perform intended human motions (e.g., moving from sitting-to-standing and normal walking). These motions require bi-directional movement of motor and a significant change in torque according to the required operation. For this, a scotch yoke mechanism is proposed for converting rotary motion from the motor (or from CVT-gearbox, after needed torque/speed adjustment) to linear motion. The linear motion is restricted according to the angular arc limits of the human joint for normal motions or as per human biomechanics, by using a four-bar mechanism. Both mechanisms and their possible uses in assistive exoskeletons are described next.

IV. SCOTCH YOKE MECHANISM

As stated, scotch yoke mechanisms convert continuous rotary motion into reciprocating linear motion, and these have been used in internal combustion and steam engines. The scotch yoke is like a crank and slider mechanism in which the linear output moves in a sinusoidal pattern, except the scotch yoke mechanisms. These have fewer moving parts and are capable of higher torques due to the unique geometrical setup of the mechanism. By virtue of this property, these are considered to be suitable for the current application. Fig. 4 demonstrates the mechanism; the motion starts with the slider all the way to the right. As the crank rotates counterclockwise, the roller attached to the crank pushes the slider to the left. After the crank has rotated 180 degrees the slider reaches the end of its range of motion and as the crank continues to rotate the slider begins to move to the right-hand side. This reciprocating motion continues if the crank rotates. When the crank speed is constant the slider reaches its

maximum velocities when the crank is at initial and final positions. Such a mechanism can be adopted to support the knee joint of an exoskeleton, as complete rotary motion is not required. The partial motion required can be provided via the reciprocating motion of the motor/CVT being converted to linear motion for feeding to another four-bar mechanism to provide the rotatory motion as discussed next.

Four-bar Mechanism

A four-bar mechanism is usually chosen to transfer motion form one link to another with some changes in torque or moment [16]. A four-bar mechanism was chosen for the application to move the joints of assistive exoskeleton such as the knee joint because the approach allows movement in normal human joint ranges to be easily accommodated. In addition, the mechanism has a polycentric nature which is especially suitable for the human motion of the knee joint [4]. Restrictions to the motion can be applied mechanically to constrain the joint movement within normal human joint movement ranges. For the knee joint, the range in the sagittal plane is 0 to 135 degrees.

During the motion from sitting-to-standing position, the lower bar is fixed (i.e., leg from the knee to the ankle or cnemis is stationary) and all other three bars are in motion whereas while walking and running the order is reversed (i.e., the lower bar is in movement, while upper bar which supports the thigh portion is at rest). The model of the four-bar mechanism used in the analysis is shown in Fig. 4 and was inspired from the design of Pons et al. [13]

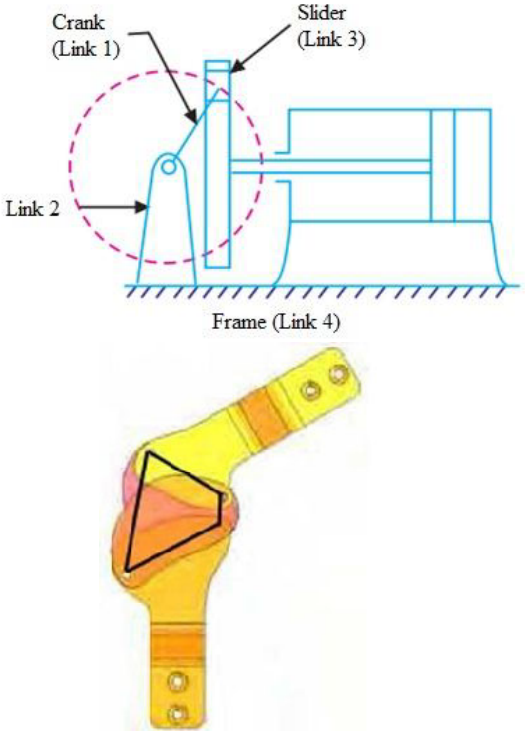


Figure 4: Scotch yoke and four bar mechanisms (Pons et al., 2007).

V. MATHEMATICAL MODELING

For mathematical modeling of the proposed hybrid mechanism, the transfer functions of the individual mechanisms are derived here and concatenated. The complete system and how the various elements are interconnected is shown in Fig. 5.

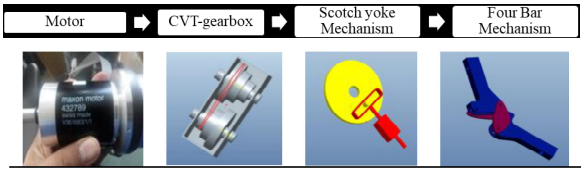


Figure 5: Human joint movement transmission system.

A 100W Maxon DC motor is used and was carefully selected keeping in mind the size, weight, and torque requirement for the knee joint. The input torque (τ) from the motor is 0.319 Nm (considering different losses) and is increased by a factor of 10 using a speed reduction belt drive coupled with motor to feed the CVT-gearbox with 3.19 Nm torque. The final output torque (τ_{sci}) obtained at the output shaft of this gearbox is given by relation between torque and diameter ratio, which was derived from the mathematical derivation of the CVT.

$$\frac{\tau}{\tau_{sci}} = \frac{d_{i'}}{d_i} \tag{1}$$

The torque exerted on the crank of the Scotch yoke mechanism by the motor is amplified by the geometry of the Scotch yoke mechanism as well as the current angle of rotation of the wheel. The relation between input and output torque of a Scotch yoke is given below and was derived from Clausen [9].

$$\tau_{fbi} = \frac{c}{psin(\theta_w)}\eta \times \tau_{sci} \tag{2}$$

where τ_{sci} is the torque applied to the Scotch yoke from the CVT-gearbox, τ_{fbi} is the input torque required at the four-bar mechanism, which was determined from biomechanics data, θ_w is the current crank angle, η is the efficiency (assumed to be 0.98, neglecting friction), p is the distance between the center of the crank and center of the roller, c is the distance between the center of the crank and the point where the steel cable connects to the leg bar. Using kinetic energy equation, one obtains the equation of motion of mechanism as follows.

The complete solution in terms of input and loading moments is explained by Yildiz et al., in which four-bar mechanism is controlled by a CVT and is given as

$$M_{l,r} = M_{in} - N\ddot{\emptyset}_2 - \frac{1}{2}\frac{dN}{d\emptyset_2}\dot{\emptyset}_2 \tag{3}$$

After combining (1), (2), (3) and solving by superposition principle, (4) can be written as:

$$M_{l,r} = \left(\frac{d_i\tau}{d_i'} \times \frac{c}{psin(\theta_w)}\eta\right) - N\ddot{\emptyset}_2 - \frac{1}{2}\frac{dN}{d\emptyset_2}\dot{\emptyset}_2 \quad (4)$$

where, M_{in} is the input moment to the four-bar mechanism which is equal to τ_{fbi}, $M_{l,r}$ is the equivalent loading moment and $N\emptyset_2$ is the equivalent mass moment of inertia. This mathematical relationship was plotted for angle and torque output vs. gait cycle % in MATLAB environment. The plots are shown in Fig. 6 and Fig. 7, respectively.

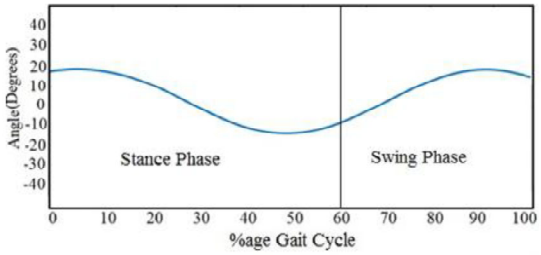


Figure 6: Position vs. % gait cycle (Analytical) for 50% assistance respectively.

The plot in Fig. 6 shows the change in the knee joint angle for normal walking. The plot crosses zero two times, once in the stance phase and other in the swing phase. So far, our design seems feasible as all criteria are met as desired. In the plot shown Fig. 7, initially there is an overshoot peak during the stance phase in almost no time due to the geometrical parameters of scotch yoke which will be optimized after experimental study and finally the torque stays between the required range after which as joint starts moving into swing phase. In next section the similar plot is obtained from simulation of the geometrical model of the proposed mechanism.

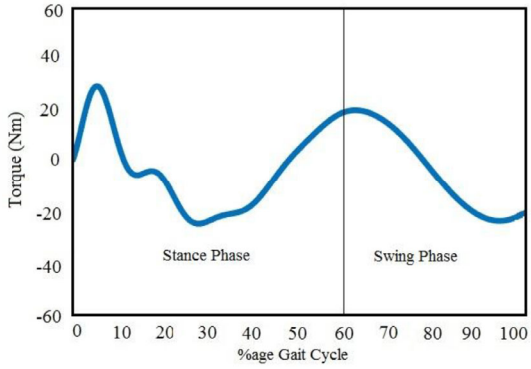


Figure 7: Knee torque vs. % gait cycle (Analytical) for 50% assistance respectively.

V. GEOMETRIC MODELING

The example for designing such a mechanism was taken from the work of Yildiz et al., where a half toroidal CVT is combined with four-bar mechanism to obtain variable input speeds. Similar kind of work with different type of CVT and other changes is presented in this paper.

To check the validity of the mathematical model (i.e., whether the transfer functions formulated above are valid or not), the geometric model of the complete assembly was developed, as shown in Fig. 8. This was then imported to MATLAB environment for simulation to obtain plots of position and torque (shown in Fig. 10 and 11).

Pro-E Wildfire version 5.0 was used to model the parts and complete assembly. It is a designing platform which is used to prepare the individual part designs and then assemble them together to model the hybrid mechanism as shown in Fig. 9.

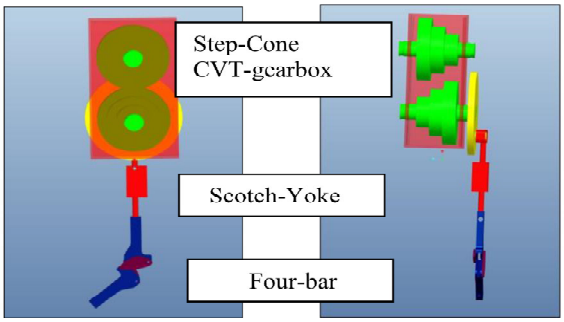


Figure 8: Different views of parts and assembly in Pro-E.

The knee joint was modelled according to specifications of a human knee [14]. These joints were assembled and contact relations between them was applied. After this, the gearbox with step conical CVT was modelled and assembled, so it could rotate with desired speed ratio according to the mathematical formulation. Next, the scotch yoke mechanism was modelled such that the linear motion of knee joint, as desired in a walking cycle, could be achieved by conversion of rotary motion from CVT. Finally, all these sub-assemblies were assembled, and simulation was performed for evaluating the dynamic behavior of the designed system.

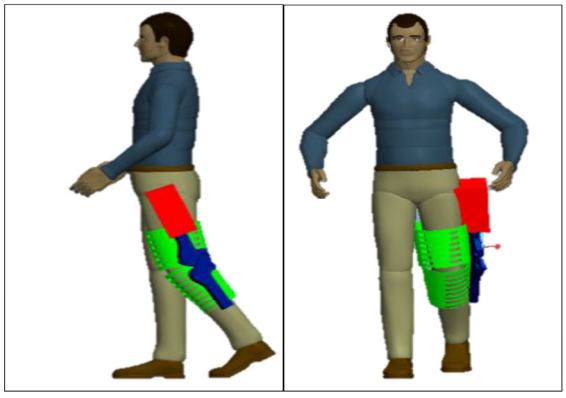


Figure 9: Assembly installed on human body, showing knee joint.

The belt drive is used to connect two steps of the step conical CVT-gearbox, and the speed ratio is kept at 0.5 for initial calculations to minimize the stress on the device. The output shaft of CVT-gearbox was

attached to a Scotch yoke mechanism and the shaft of which was attached to the designed four-bar knee joint. This study is restricted to only walking gait cycle (i.e., sitting and standing motions are not taken into consideration) because currently we are working with condition where the upper bar is considered as the fixed link. Thus, the movement of other three bars execute the motions of the four-bar mechanism and resembles the pattern similar to the joint angle under study for the motion being performed (e.g., knee joint angle during walking gait cycle). After this, the complete assembled model was installed on a Manikin (virtual human model) as shown in Fig. 10, to see the feasibility of the approach by obtaining static simulation movies for the integration of the overall design during human walking. The weight of the complete assembly for one leg, as checked in Pro-E, is 16 kg. For the initial studies the material to make the device is Aluminum alloy (Al-7075), whose properties are presented in Table 1.

Material	Property	Value	Units
Aluminum Alloy (Al - 7075)	Mass density	2810	Kg/m^3
	Yield Strength	503	MPa
	Ultimate tensile strength	572	MPa
	Young's modulus of elasticity	71.7 GPa	GPa

Table 1: Material properties for Aluminum [22].

For performing the simulation, the CAD model of the knee was exported from Pro-E to Simulink and a saturation block was applied to limit upper and lower values resulting from the scotch yoke mechanism. Normal range of motion at the knee is considered to be 0 degrees of extension (completely straight knee joint) to 135 degrees of flexion (fully bent knee joint). Walking requires complete knee extension as the heel strike and up to 60 degrees of flexion range with maximum peak value of 20°. One complete walking cycle consists of two phases (i.e., stance and swing phase).

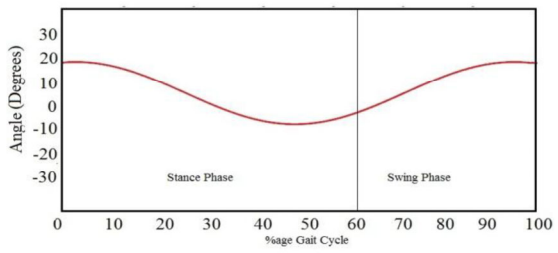


Figure 10: Position vs. % gait cycle (simulation) for 50% assistance.

Plots of the knee joint angle and torque trajectories were obtained via Simulink and are shown in Figures 10 and 11 respectively. The normal starting position for the knee angle was chosen to be 20° when the toe comes in contact with the ground and then completes both the phases of a walking cycle and a new cycle can begin. The Simulink results are shown in Fig. 10, where it can be seen that the range of knee angle motion is 60° [20° to 0°, 0° to -10°, -10° to 0° and 0° to 20°] and the peak angle value is 20°. At the beginning of a walking cycle, joint angle starts at 20° and decreases to zero in the stance phase, which is much smaller as compared to the swing phase, in which knee extension takes place and at its end, the knee starts to reach out again to its initial position. From the simulation, it can be inferred that cycle progresses with much smoother variation thus giving the better control over the designed knee joint of the exoskeleton structure. Fig. 11 presents the torque vs. gait cycle.

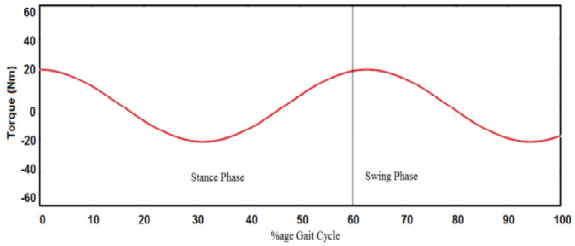


Figure 11: Torque vs. % gait cycle (simulation) for 50% assistance.

VI. SIMULATION RESULTS AND VALIDATION

In this section, validation of plots is carried out where both results obtained from mathematical modelling and geometrical modelling are compared with biomechanical walking data published in the literature, which is taken as reference trajectory [4]. This was done by superimposing the MATLAB/Simulink simulation results against normal human walking data. Figs. 12 and 13 shows the comparison between the results obtained from the mathematical transfer function, the geometrical model obtained via MATLAB/Simulink and normal human walking data. Fig. 12, shows the knee joint's angle trajectory showing the models are able to control the limits of knee motion well within the 60° range. The starting and final knee angle is also the same, which concludes that design of the proposed mechanism here is effective as other types of controllers. The main difference observed was the slight change in the duration of the stance phase and how the slope of the graph varies. Further improvement could be done in future work by trying better strategies and improvement in design. In the second case, in order to verify the torque variations, the results are compared with the normal human walking torque data as shown in Fig. 13.

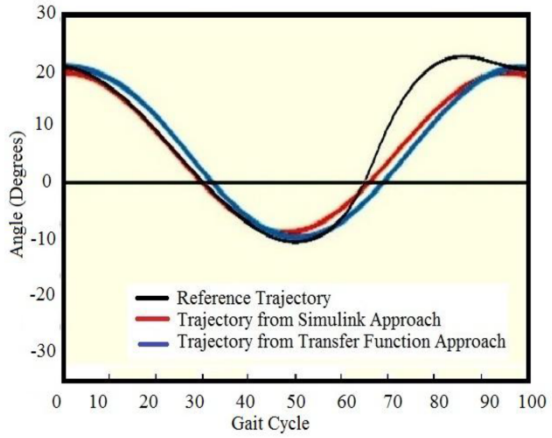


Figure 12: Knee angle trajectory vs. gait cycle for 50% assistance.

From experimental tests carried out, it was found that for a knee exoskeleton, the torque needed is 20 Nm to 26 Nm during the walking cycle [4]. The simulation results have been obtained using the hybrid mechanism and are found in close agreement, except for the initial overshoot, which is nearly 20 Nm, where the initial condition is the point of maximum angle covered by knee joint in forward direction. From the above figures, it can be seen that results are obtained for 50% assistance for two speed ratios of CVT-gearbox as discussed. In the first case, the results are obtained when the speed ratio of this gearbox is equal to one. Therefore, the dynamics of the CVT added and classical four-bar mechanism are compared in the same conditions. In second case, the results are obtained for 0.5 speed ratio which has effect on fluctuations on position and torque ranges because in this case the designed system is intended to provide just one fourth of assistance required by human being.

The simulation results show that using a CVT-gearbox for obtaining variable input speed in conjunction with a scotch yoke mechanism and a four-bar linkage is feasible under all circumstances.

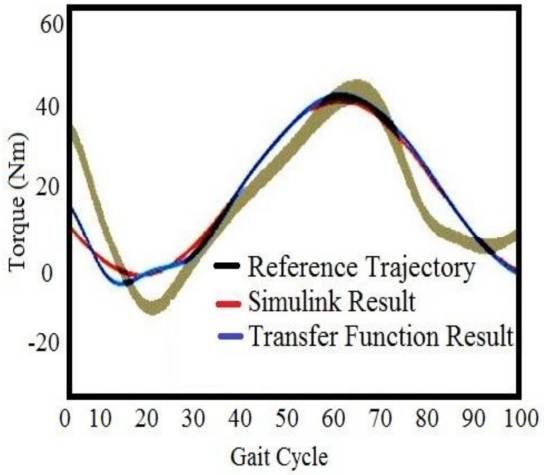


Figure 13: Torque vs. walking cycle validation for 50% assistance.

The stance and swing phase with respect to % gait cycle are explained in Fig. 14.

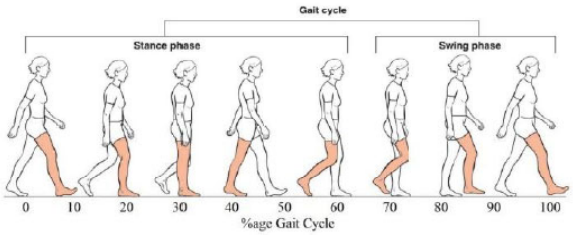


Figure 14: Stance Phase and Swing Phase.

CONCLUSION

A novel design of a four-bar mechanism equipped with a CVT-gearbox has been proposed. This design is simpler compared to the existing complex control mechanism. The new design can obtain variable input speeds to achieve desired walking trajectories. Although the approach is viable technically, the mass of the mechanisms is large, which can be a significant issue. To overcome this, the new hybrid mechanism was designed based on average human gait cycle by optimizing the weight of mechanical components where possible. The dynamics of the new design have been solved using MATLAB/Simulink and the results obtained agree with normal human walking data. The results indicate that it is possible to use a CVT to change the motor gearing at the knee joint of an assistive exoskeleton and associated mechanisms, instead of using conventional motor speed control.

Further design optimization work is planned to reduce device weight as well as to control flexion and extension more accurately. The choice of materials could also be investigated to help reduce device weight.

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