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Multi-objective Optimization of Force Transmission Quality and Joint Misalignment of a 5-Bar Knee Exoskeleton

Ahmed Asker[1,2], Shengquan Xie[1] and Abbas A. Dehghani-Sanij[3]

Abstract— **The ability to follow a normal anatomical motion is one of the fundamental design requirements of wearable exoskeleton. Human knee motion is a combination of sliding and rolling actions, which can not be replicated by a simple kinematic pair with a fixed rotation axis. In this paper, a polycentric robotic knee exoskeleton is designed based on the 5-bar mechanism (5-BM) to reproduce knee motion. The Genetic Algorithm finds the optimum parameters of the 5-BM by minimizing a weighted cost function which consists of the average Joint Force Index (JFI) and the misalignment between the centre of rotation of the exoskeleton and the user's knee. An average and maximum ICR error of 0.16mm and 0.43mm is obtained by the optimized 5-BM. It yielded an average actuation toque of 7.33N.m and JFI of 4.88 compared to 217.73N.m and 6.04 obtained by the widely used 4-BM.**

I. INTRODUCTION

Injuries and ageing significantly reduce mobility and quality of life of millions of people worldwide [1]. Robotic mobility assistive devices have a high potential to alleviate the socio-economical effects that result from population ageing. Exoskeletons are wearable devices able to augment healthy people and offer assistance to mobility-impaired people. Many factors are considered during the design of exoskeletons such as the type of actuation, structure weight, sensory feedback, metabolic cost and ergonomics. The user's safety and comfort are the most important design requirements that have to be addressed from the early stages of the design. Proper alignment between the axis of rotation of the user and exoskeleton joints is a key design issue, which affects both safety and user acceptance. Misalignment leads to an undesirable pistoning force which can lead to discomfort or injuries [2], and increase the abandonment of the exoskeletons by their users [3].

The human knee is the main motor joint of the lower limb and has a major role in weight-bearing and ambulation. Diseases such as osteoarthritis and injuries such as ligament and meniscus damage can affect the function of the knee. Assistive devices can help those people to restore their motion capabilities [2]. The knee joint has a complex motion that involves flexion/extension, abduction/adduction and internal/external rotation. The main movement of the knee joint is flexion/extension in the sagittal plane, which is a combination of sliding and rolling. This motion results from the shape of the femur and tibia condyles and the anatomy of the cruciate ligament [4]. Thus, the instantaneous centre of rotation (ICR) changes as the knee is flexed.

In the literature, many mechanisms have been proposed to design a polycentric knee exoskeleton that mimics the motion of the human knee, hence reducing the pistoning force. In [5], a geared 5-Bar Mechanism (5-BM) was used to design a polycentric bionic knee exoskeleton, but the position of its ICR relative to the knee was not reported. In [6], the passive Degrees of freedom (DOF) of Schmidt coupling was used to self-aligning translation of the ICR of the knee. In [7], a self-aligning knee based on 3-RRP mechanism was developed. Regrettably, these designs were complex and bulky. Since the sagittal plane motion generated by the cruciate ligaments with the femur and the tibia can be approximated by a crossed 4-bar linkages [4], many bionic knee joint designs were based on the 4-bar mechanism (4-BM) [8], [9], [10]. In [9], the genetic algorithm was used to find the optimal parameters of a 4-MB that minimize the difference between a reference ICR path of the human knee developed in [11] and ICR of the mechanism. This optimised mechanism accurately replicated the reference path. Regrettably, misalignment is the only criterion that was considered, and other designed objective such as the quality of force transmission had not been addressed in the literature. Force transmissivity is a measure of the effectiveness of the power flow from the input to the output. It is an important performance index that can be used as an objective function during mechanism synthesis [12] to reduce the required input force/torque to resist certain forces/moment applied at the output link.

This paper presents the design of a knee exoskeleton based on the 5-BM. The dimension synthesis problem is formulated as a weighted cost function of the error between the ICR of the exoskeleton and the reference path of the human knee ICR and the average Joint Force Index (JFI). As the JFI depends on the magnitude and direction of the applied forces/torque, it is calculated based on the assistance force required during sit-to-stand (STS) motion to compensate for the gravitational torque due to user's weight. The quality of force transmission is evaluated for the STS activity since the required assistance torque is higher than the other mobility activities such as walking [13]. The Genetic algorithm is adopted to solve the optimization problem and the performance of the optimised mechanism is compared with the crossed 4-BM, which is

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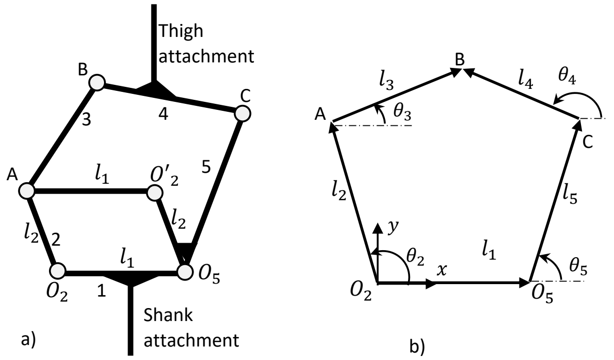

Fig. 1. The proposed 5-MB base knee joint mechanism a) Schematic of the proposed mechanism , b) Position vector loop for the 5-BM

widely employed for knee exoskeletons and orthoses. The rest of the paper is organised as follow; conceptual design and kinematic analysis are presented in Section II. In Section III, the force analysis of the proposed knee joint mechanism is performed. Section IV describes the formulation of the optimal dimensional synthesis problem. Results are presented, and the performance of the optimised 5-BM is compared with the well-known 4-BM. Finally, Section VI is the conclusion.

II. CONCEPTUAL DESIGN AND KINEMATIC ANALYSIS

The 4-BM is widely used for designing polycentric knee joints, but according to the best of the authors' knowledge, the quality of force transmission has not been studied yet. Compared to the 4-BM, the 5-BM can be designed to trace more complex coupler curves and has more design variables to be optimised [14]. Since the 5-BM has 2 DOFs, the rotation of the two links connected to the ground is coupled by a gear train such that gear ratio control the rotational velocity of those two links. According to Chebyschev, any 4-BM coupler curve can be duplicated with a geared 5-BM with a gear ratio of one [15]. At least three gears are needed to design a gear train with a gear ratio of one or an internal gear has to be used. Furthermore, gears are a delicate component which is quite bulky and expensive. The schematic of the proposed 5-MB base polycentric knee mechanism is shown in Fig. 1 a). The Links O_2O_5, O_2A, AB, BC and CO_5 forms the links of the 5-BM and are numbered from 1 to 5, and θ_i represent the angle of link i relative to the positive x-axis. The thigh attachment is rigidly attached to the coupler link 4 (BC), while the thigh attachment is rigidly attached to the ground link 1 (O_2O_5). The links O_2O_5, O_2A, AD and O'_2O_5 forms a parallelogram that couples the motion of Links 2 and 5. As links DO_5 and CO_5 are rigidly attached, links O_2A and CO_5 constrained to have the same rotational velocity. Thus, the closed kinematic chain O_2ABCO_5 is equivalent to a geared 5-BM with a gear ration of one $(n = 1)$.

As the only role of the links AO'_2 and O'_2O_5 is to couple the rotation of links 2 and 5, they are excluded from the kinematic analysis. The vector closure method is used to find θ_3 and θ_4 (Fig. 1 b)) for a given links' length, input angle θ_2 and initial angular positions of links 2 and 5 $\left(\theta_2^0, \theta_5^0\right)$. Referring to Fig. 1 b), The closed chain O_2ABCO_5 can be written in the vector form as follows:

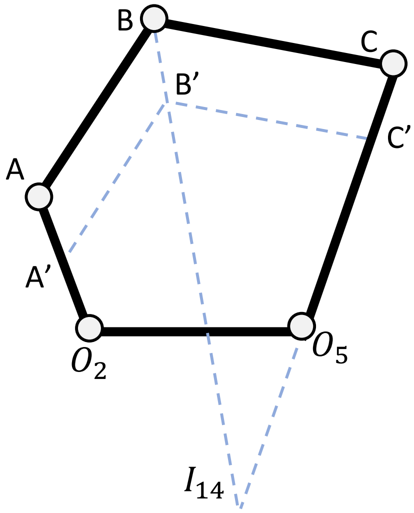

Fig. 2. Procedures for obtaining I_{14}.

$$\overrightarrow{O_2A} + \overrightarrow{AB} - \overrightarrow{O_2O_5} - \overrightarrow{O_5C} - \overrightarrow{CB} = 0 \tag{1}$$

Which can be more conveniently formulated in terms of the link's length l_i and angle θ_i (Fig. 1 b)) as follows:

$$\sum_{i=1}^{i=5} \rho_i l_i \mathbf{u_i} = 0; \quad \text{for} \quad i = 1, 2, \ldots, 5 \tag{2}$$

where

$$\mathbf{u_i} = [cos\theta_i \quad sin\theta_i]^T \text{ and } \rho = \begin{cases} 1 & i=2,3 \\ -1 & i=1,4,5 \end{cases}$$

The value of angles θ_3 and θ_4 can be obtained using half-angle substitution [16] as follows:

$$\theta_3 = 2\left(atan2(-e_1 - \sqrt{e_1^2 + e_2^2 - e_3^2}, e_3 - e_2)\right) \tag{3}$$

$$\begin{aligned} \theta_4 =& atan2(-l_1 \sin\theta_1 + l_2 \sin\theta_2 + l_3 \sin\theta_3 - l_5 \sin\theta_5, \\ & - l_1 \cos\theta_1 + l_2 \cos\theta_2 + l_3 \cos\theta_3 - l_5 \cos\theta_5) \end{aligned} \tag{4}$$

where

$$\theta_5 = \theta_2 - \theta_2^0 + \theta_5^0$$

$$e_1 = -2l_3(l_1 sin(\theta_1) - l_2 sin(\theta_2) + l_5 sin(\theta_5))$$

$$e_2 = -2l_3(l_1 cos(\theta_1) - l_2 cos(\theta_2) + l_5 cos(\theta_5))$$

$$\begin{aligned} e_3 =& l_1^2 + l_2^2 + l_3^2 - l_4^2 + l_5^2 - 2l_1l_2cos(\theta_1 - \theta_2) \\ & + 2l_1l_5cos(\theta_1 - \theta_5) - 2l_2l_5cos(\theta_2 - \theta_5) \end{aligned}$$

The ICR of Link CB relative to O_2O_5, I_{14}, is found using the angular velocity vector method adopted in [17]. As shown in Fig. 2, the points A' and B' are obtained by the ratio between the angular velocity of link 2 and 5 as shown in Fig. 2. Thus, in the proposed 5-BM, the ratio $\left(\frac{AA'}{CC'}\right)$ is

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -l_2 s_2 & l_2 c_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -l_3 s_3 & l_3 c_3 & 0 & 0 & 0 & 0 & l_3 s_3 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & l_4 s_4 & -l_4 c_4 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & l_5 s_5 & -l_5 c_5 & 0 & 0 & l_2 s_2 & 0 \end{bmatrix} \begin{bmatrix} F_{12x} \\ F_{12y} \\ F_{32x} \\ F_{32y} \\ F_{43x} \\ F_{43y} \\ F_{54x} \\ F_{54y} \\ F_{15x} \\ F_{15y} \\ F' \\ T_{12} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -F_x \\ -F_y \\ M + \frac{l_4}{2}\left(s_4 F_x - c_4 F_y\right) \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

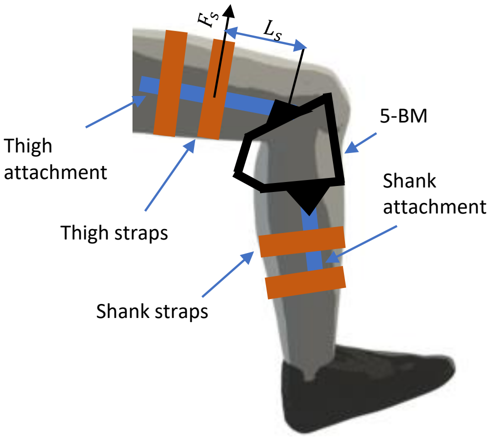

Fig. 3. The knee exoskeleton with the proposed 5-BM.

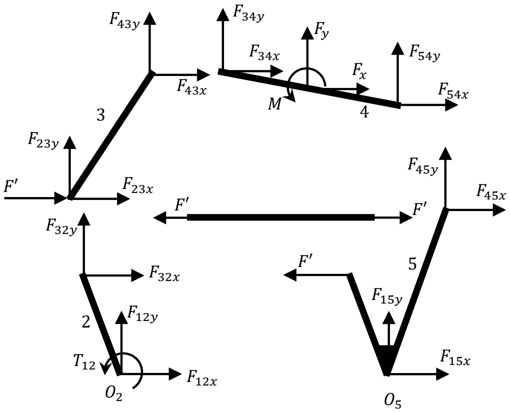

Fig. 4. The free-body diagram of the propose knee mechanism.

equal to one. The point B' is obtained by intersecting a line parallel to AB and passing through A' with a line parallel to BC and passing through C'. According to Kennedy-Aronhold Theorem [18], I_{14} is the point of intersection between $\overrightarrow{AA'}$ and $\overrightarrow{CC'}$. This procedures are implemented using the MATLAB® symbolic toolbox, and the closed form solution is obtained as follows:

$$\begin{bmatrix} I_{14x} \\ I_{14y} \end{bmatrix} = \begin{bmatrix} Cx + \frac{nl_4 l_5 \sin(\theta_3 - \theta_4)\cos(\theta_5)}{l_2 \sin(\theta_2 - \theta_3) + nl_5 \sin(\theta_3 - \theta_5)} \\ Cy + \frac{nl_4 l_5 \sin(\theta_3 - \theta_4)\sin(\theta_5)}{l_2 \sin(\theta_2 - \theta_3) + nl_5 \sin(\theta_3 - \theta_5)} \end{bmatrix} \tag{5}$$

where (I_{14x}, I_{14y}) and (Cx, Cy) are the ICR position of link 4 relative to link 2 and position of point C, both measured in O_2xy coordinate frame.

III. FORCE ANALYSIS

The purpose of the force analysis is to obtain the reaction forces needed to resist the assisting force/moment at link 4. The attachment of the proposed mechanism to the human leg is shown in Fig. 3. The shank and thigh attachments are fixed to the middle of links 1 and 4, respectively. During this analysis, the shank is considered fixed to the ground and the knee is flexed by the force, F_s, applied by the thigh strap at distance L_s, which causes forces F_x and F_y and moment M acting at link 4. In this design, we assume $L_s = 10$cm [2], and F_s is perpendicular to the thigh attachment. The inertia and gravitational forces are considered small compared to the applied force and are not included in this analysis since the mechanism is not designed for high velocity. The force analysis is performed using the procedures described in [18]. The equations of static equilibrium for each link are formulated using the free body diagram of the mechanism shown in Fig. 4. The linear system of equation presented in (6) is obtained by simplifying the equilibrium equations using the fact $F_{ij} = F_{ji}$, where F_{ij} is the reaction force on link j exerted by link i. In (6), c_i and s_i stand for $\cos\theta_i$ and $\sin\theta_i$, respectively.

IV. OPTIMAL DIMENSIONAL SYNTHESIS OF THE 5-BM

A. Reference path of the knee ICR

In this section, the knee motion's parameters of adults obtained in [19] are briefly described. These parameters were calculated for flexion angle, $\beta \in [0° \quad 120°]$ using the best-fit quadratic equations as follows [19]:

$$\begin{aligned} V =& 0.0791\beta - 5.733 \times 10^{-4}\beta^2 \\ & - 7.682 \times 10^{-6}\beta^3 + 5.759 \times 10^{-8}\beta^4 \end{aligned} \tag{7}$$

$$I = 0.3695\beta - 2.958 \times 10^{-3}\beta^2 + 7.666 \times 10^{-6}\beta^3 \tag{8}$$

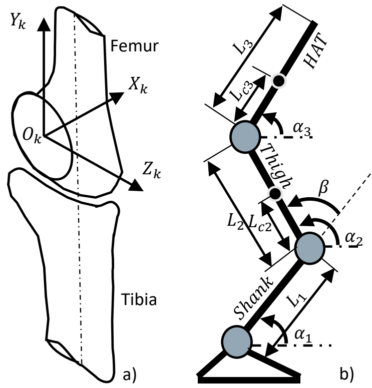

Fig. 5. a) Reference coordinate frame for modelling the knee ICR [20], b) The 4-links model used to analysis STS motion.

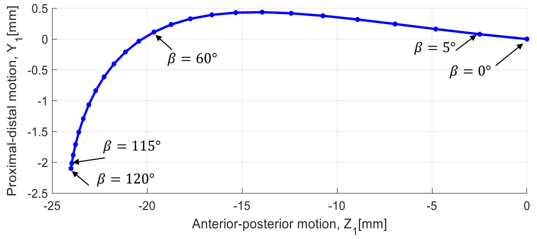

Fig. 6. Proximal-distal and anterior-posterior motions of the knee ICR.

$$T_{PD} = -0.0683\beta + 8.804E - 4\beta^2 - 3.750 \times 10^{-6}\beta^3 \quad (9)$$

$$T_{AP} = -0.1283\beta + 4.796 \times 10^{-4}\beta^2 \quad (10)$$

where V, I, T_{PD} and T_{AP} are knee varus rotation, internal rotation, proximal-distal translation and anterior-posterior translation, respectively.

The position of the knee ICR in the sagittal plane, (Y_k, Z_k) can be obtained using (7) through (10) as follow [19]:

$$\begin{bmatrix} Y_k \\ Z_k \end{bmatrix} = \begin{bmatrix} -\sin(V)X_k + T_{PD} \\ \cos(V)\sin(I)X_k + T_{AP} \end{bmatrix} \quad (11)$$

where X_k is the lateral distance measured from frame $O_k x_k y$ as shown in Fig. 5 a). Since the exoskeleton is laterally attached to the user's knee, the distance $X_k = 60mm$ is assumed in this analysis [20]. The angle and length units utilized in this section are degree and mm, respectively. A plot of the proximal-distal and anterior-posterior motions of the knee ICR is shown in Fig. 6.

B. Reference Knee Torque

Sit-to-stand (STS) is one of the most frequent mobility tasks which involves a very high knee joint torque. In this analysis, the required knee torque to resist the forces due to gravity is obtained. This torque is used with the force analysis performed in Section III to calculate the JFI of the 5-BM. Since dynamic forces account for less than 10% of the force needed to perform the STS motion [21], only gravitational forces are considered here. The 4-links model [22] shown in Fig. 5b) is used to represent the human body during STS motion. The four links are namely: foot, shank, thigh, and HAT (Head Arms and Trunk). The foot is assumed to be fixed during the STS motion, and the length of each segment is calculated from the user stature height as described in [22]. The knee torque needed to overcome gravity is obtained using Lagrange's formulation as follow:

$$T_2 = g\left[(M_2 L_{c2} + M_3 L_2)\cos\alpha_2 + M_3 L_{c3}\cos\alpha_3\right] \quad (12)$$

where L_1, L_2, L_3 L_{C2}, L_{C3}, α_2 and α_3 are defined in Fig. 5b), while M_2 and M_3 are the mass of the thigh and HAT Links, respectively.

The STS data of a subject who has a height of $175cm$ and weigh $79kg$, is used to obtain the knee torque as a function of the flexion angle ($\beta = \alpha_2 - \alpha_1$). The calculated torque is shown in Fig. 7. The experimental procedures used to obtain the STS data are presented in [23].

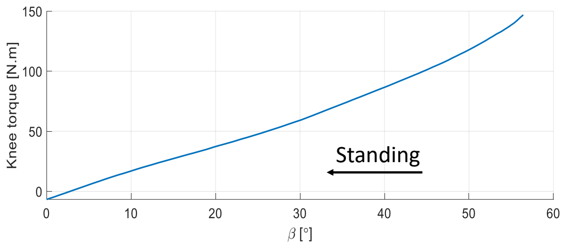

Fig. 7. The required knee torque of during STS motion.

C. Joint Force Index

Many indices have been proposed in the literature to assess the effect of certain external loads on the force transmission of a mechanism [12]. In this section, the JFI is used for its simplicity and it's ability to consider the worst force transmission within the joints of the mechanism. It can be applied to any mechanism regardless of its complexity. According to [24], the JFI is defined as follows:

$$JFI = \max\left|\frac{F_{ij}}{F_s}\right|; \qquad \text{for all pairs}, i, j \quad (13)$$

where F_{ij} represents the magnitude of the joint force, and F_s is the external load.

It is apparent from 13 that the smaller the value of the JFI the better the quality of the force transmission.

D. Optimal dimensional synthesis

The goal of dimensional synthesis is to find the geometric parameters of the 5-BM that enable mimicking the anatomical motion of the knee joint while ensuring a good power flow from the input to the output is achieved. As shown in Fig. 1, the kinematic of the 5-BM is determined by link's length (l_i; for $i = 1, 2, \ldots, 5$), and the initial angular positions of links 2 and 5 $\left(\theta_2^0, \theta_5^0\right)$. These parameters control the performance of the 5-BM and can collectively represent the design variable vector, $\chi = \left[l_1 \; l_2 \; l_3 \; l_4 \; l_5 \; \theta_1^0 \; \theta_5^0\right]^T$. A weighted sum cost function of the error between the proposed mechanism ICR (I_{14}) and the reference knee ICR developed in Section

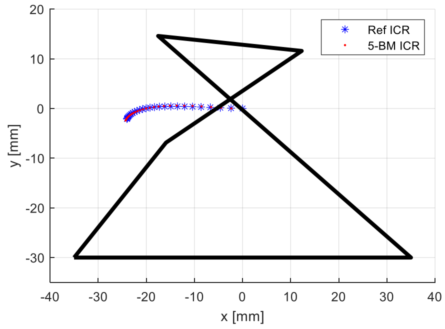

Fig. 8. The optimal 5-BM with the reference and synthesized ICR.

IV-A, and the average JFI described in Section IV-C. The cost function is formulated as follows:

$$C = w_1 \sum_{\beta=0^\circ}^{120^\circ} \sqrt{\left(I_{14x}(\beta) - Y_k(\beta)\right)^2 + \left(I_{14y}(\beta) - Z_k(\beta)\right)^2} + w_2 \sum_{\alpha_2=\alpha_2^0}^{\alpha_2^f} JFI(\alpha_2) \tag{14}$$

where α_2^0, α_2^f are the value of the knee angle (Fig. 7) at start and end of the STS motion, while $w_1 = \frac{1}{N}$ and $w_2 = \frac{1}{32N_s}$ are the weights of the error and torque terms, respectively. Note that, w_1 and w_2 is used as a normalization factor to give each term of the objective function the same weight during searching for the minimum value, where $N = 25$ and N_s are the total number of point at which ICR is evaluated and the number of point whithin the STS motion range, respectively.

The following steps are employed to calculate the value of the objective function. First, the exoskeleton is assumed to be at the initial configuration ($\theta_2 = \theta_2^0$ and $\theta_5 = \theta_5^0$) when the knee is fully extended ($\beta = 0^\circ$). Then, the angle of the input link, θ_2 is incrementally increased until the angle θ_4 is increased by 120° relative to the initial configuration. That determines the configurations of the 5-BM for $\beta \in [0^\circ \quad 120^\circ]$. The ICR of the mechanism is evaluated at each configuration using (5) and compared with the reference ICR given in (11). The linear system presented in (6) is solved at each configuration where $\alpha_2 \in [\alpha_2^0 \quad \alpha_2^f]$. Finally, the objective function is evaluated using (14).

Consider the manufacturability and aesthetic requirements of the exoskeleton, the links length are constrained as follow:

$$30\text{mm} \leq l_i \leq 80\text{mm}; \quad i = 1, 2, \ldots, 5 \tag{15}$$

The problem is implemented in MATLAB® and solved by the Genetic Algorithm (GA) with the default parameters. The optimal dimensions vector, χ^* are obtained as follows:

$$\chi^* = [70 \ 30 \ 34 \ 30 \ 69 \ 0.88 \ 2.44]^T$$

where length and angle units are set to mm and radian, respectively.

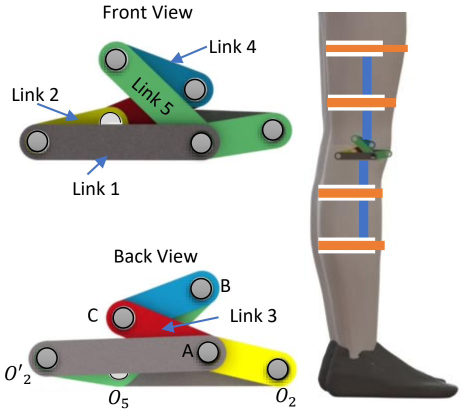

Fig. 9. 3D model of the optimised 5-BM.

V. Results and Discussion

In this section, the performance of the optimised 5-BM is evaluated and compared with the 4-BM described in [9]. The static force analysis of the 4-BM is performed using the same procedures used to analysis the 5-BM in Section III. The optimised 5-BM along with reference and synthesized ICR is shown in Fig. 8, while the 3D model of the knee exoskeleton is shown in Fig. 9. The schematic of the 4-BM developed along with its geometric dimensions is shown in Fig. 10.

Both mechanisms are assumed to be actuated by a motor that rotates link 2 and evaluated based on the reference torque obtain in Section IV-B, which represent 100% of the torque needed to accomplish the STS task. Thus, the torque required to actuate one side exoskeleton will be about half the value reported in this section. The optimised 5-BM yields average and maximum ICR error of 0.16mm and 0.43mm, respectively. The 4-BM yields a maximum error of 1.06mm, as reported in [9]. The required actuation torque and JFI for the two mechanisms are evaluated and presented in Fig. 11. The average actuation toque and JFI are 7.33N.m and 4.88 for the optimised 5-BM and 217.73N.m and 6.04 for the 4-BM. It can be seen from Fig. 11 that the crossed 5-BM has better force transmissibility, especially at the onset of the STS motion (knee is flexed) where the required knee torque is high. In contrast, the 4-BM has a better JFI at the end of the STS motion (knee is extended) when the knee torque is very low. In fact, these results would be different if the external load or actuation method is changed. The aim of this work is not limited to design a polycentric knee with enhanced performance. It also provides a method for optimising planer mechanisms to fulfil certain design criteria while ensuring a good force transmission is achieved.

VI. Conclusion

A polycentric knee exoskeleton is designed based on 5-BM to mimic the human knee motion. The GA is used to obtain the optimal dimensions of the proposed mechanism that simultaneously reduce the misalignment between the ICR of the 5-BM and the human knee while maximizing force

L_1	44.5mm
L_2	51.6mm
L_3	40.9mm
L_3	47.2mm
ψ_3	27.5°
ψ_1	19.5°

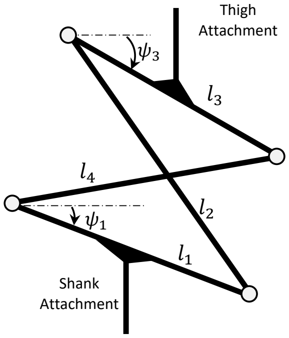

Fig. 10. Geometric parameters for the 4-BM described in [9].

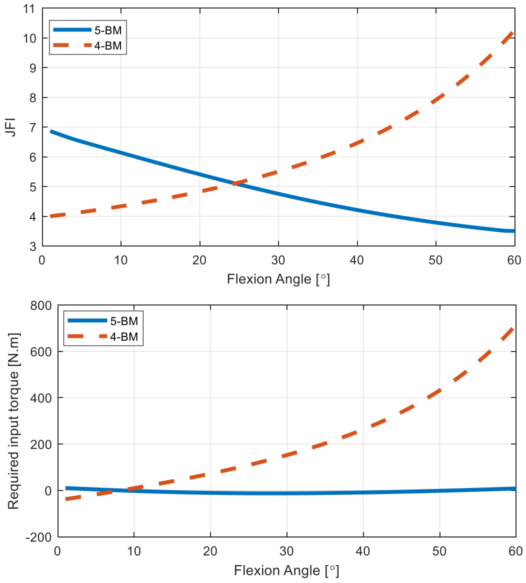

Fig. 11. The actuation torque and JFI during STS assistance by the optimized 5-BM and the 4-BM.

transmission from the input link to the output link. The optimised 5-BM shows a satisfactory performance in terms of average JFI and the input torque required to assist the user during STS motion. The analysis performed in this paper provides a systematic approach for designing bio-mimicking mechanisms with a high force transmission quality. The procedures employed for the dimensional synthesis of the 5-BM is generic and can be applied to other design problems.

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