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Review Article

A Review on Compliant Joint Mechanisms for Lower Limb Exoskeletons

Miguel A. Gálvez-Zúñiga and Alejandro Aceves-López

Tecnologico de Monterrey, CEM, 52926 Atizapan, Mexico City, Mexico

Correspondence should be addressed to Miguel A. Gálvez-Zúñiga; a01160915@itesm.mx

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Lower limb exoskeletons are experiencing a rapid development that may suggest a prompt introduction to the market. These devices have an inherent close interaction with the human body; therefore, it is necessary to ensure user's safety and comfort. The first exoskeletal designs used to represent the human joints as simple revolute joints. This approximation introduces an axial misalignment issue, which generates uncontrollable internal forces. A mathematical description of the said misalignments is provided to better understand the concept and its consequences. This review will only focus on mechanisms aiming to comply with its user.

1. Introduction

Lower limb exoskeletons (LLE) are a type of humanoid service robot designed to improve its user's physical performance, commonly during locomotion. As the name implies, the support is given to the lower limbs through the ankle, knee, and/or hip joints by means of actuated wearable mechanisms.

According to its application, LLE can be classified as augmentation, rehabilitation, or assistive exoskeletons. The first category aims to enhance characteristics of the human movement such as strength [1], endurance [2], speed [3], or metabolic cost [4–6]. This kind of exoskeleton is of great interest to the military as established by the development of systems such as the Berkeley Lower Extremity Exoskeleton (BLEEX) [7], Human Universal Load Carrier (HULC) [8], Hercule [9] and XOS2 [10].

The rehabilitation category focuses on restoring motion function and improving gait patterns of patients affected by spinal cord injuries [11], strokes [12], foot drop [13], or even poliovirus [14]. The exoskeletons belonging to this category specifically help to provide the therapy needed to (partially) restore normal gait. This can be achieved, for example, by controlling the trajectory or torque of each user's joint independently [15]. This category can be illustrated by Lokomat [16], Active Leg Exoskeleton (ALEX) [17], ReoAmbulator [18], and Lower Extremity Powered Exoskeleton (LOPES) [19].

Lastly, assistive exoskeletons' objective is to compensate physical disabilities caused by any sort of injury, trauma, or weakness. Taking this into account, only the impaired joints should be artificially supported by the robot, keeping the others unaffected. Robots like ReWalk [20], Hal-5 [21], and Ekso [22] belong to this category.

In the past ten years, this type of technology has been the subject of an increasing number of publications (Figure 1). According to Scopus [23], just in 2014 there were more works associated with lower limb exoskeleton than the accumulated publications between 1995 and 2010 (120 versus 110 published items).

The rapid development is a result of advances in actuators, sensors, materials, batteries, and computer processors. These innovations had led Ferris [24] to state that, by 2024, people will be walking down the street, in the malls, and to their homes wearing robotic exoskeletons in a portable, svelte, and fashionable way. However, it is yet a long way until we can seize the full potential of exoskeletons.

There are still many things not completely understood about the physiology and biomechanics of human movement [25]. This unawareness makes it impossible, for example, to

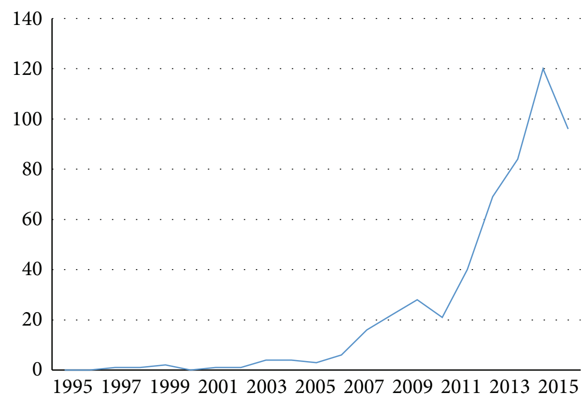

FIGURE 1: Publications per year reported in citation indexing service Scopus [23] when searching for the term lower limb exoskeleton.

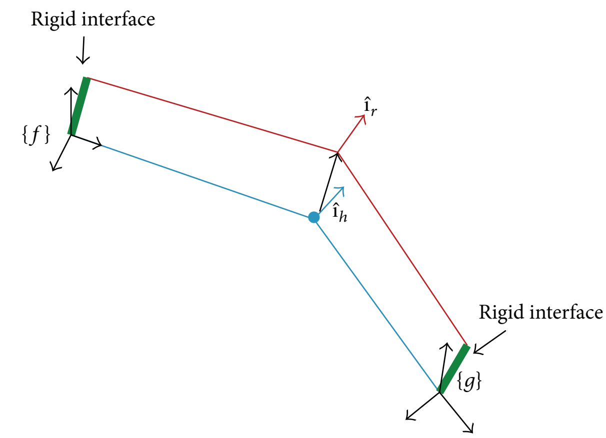

FIGURE 2: Representation of the simplified close kinematic chain formed by the exoskeleton (human in blue, robotic in red).

predict how exoskeletons will affect locomotion when there is little knowledge of the cognitive mechanism involved in the process [26]. Therefore, to fulfill Ferris' vision, researchers must overcome several challenges in all areas of expertise associated with exoskeletons: control, instrumentation, computer science, electronics, and mechanics.

Irrespective of the different application fields, exoskeletons share a main objective for a proper functioning: transfer power to the user's limb. Additionally, due to the close interaction between robot and user, the robots must assure safety of its wearer without compromising their own efficiency. Both concepts relate directly to the mechanical aspect of exoskeletons and will be the main focus for this paper.

Mechanically, the robot must provide support so that the added weight, of either the loads or the exoskeleton itself, does not affect the user. It also must adapt to the wearer's anatomy so it is beneficial for a wide range of the population. All of this while maintaining a small size to ensure its portability.

2. The Axial Misalignment Problem

There are two main concerns when designing the physical part of an exoskeleton. The first one is the added mechanical impedance to the legs which, in absence of a specialized control scheme that masks the inertia, hinders the user's agility and increases the metabolic energy consumption [27]. The other is the mismatch between the human and robotic joints which cause kinematic incompatibility. We focus on the latter as it compromises the user's safety and comfort.

According to Chasles' theorem, the motion of any rigid body can always be expressed as a translation along a line followed by a rotation about the same line. In screw theory, said line can be obtained by a twist which is a six-dimensional vector that represents all the velocities of a body. This twist, as any other vector, is formed by magnitude and a unit vector. The first takes the value of the angular velocity, while the latter is a combination of the pitch (which is the ratio of linear velocity to its angular counterpart) and a Plücker line. The said line describes the position and orientation of an infinite line that can be interpreted as the *instantaneous axis of rotation* (IAR), an extension of the Instantaneous Center of Rotation in planar movement, which is also the line described by the theorem.

Additionally, in any open kinematic chain, no matter the number of links, there is a twist (T_c) that describes the movement of the final link of the chain relative to its first. It is equal to the sum of the twists (T_x) of every joint that conforms the chain

$$T_c = T_1 + T_2 + \cdots + T_n. \tag{1}$$

The case is quite different for close kinematic chains; adding every twist in the chain would imply calculating the velocity of a body relative to itself, which is zero:

$$T_1 + T_2 + \cdots + T_n = 0. \tag{2}$$

Individually, exoskeletons and human limbs are both open chains, each one having a characteristic twist, ${}^{f}T_{g}^{(R)}$ and ${}^{f}T_{g}^{(H)}$, respectively, that describes the instantaneous velocities of body $\{g\}$ relative to the reference body $\{f\}$.

The exoskeletal application inherently requires connecting both chains together, thus forming one closed kinematic chain. Figure 2 is a representation of the said kinematic chain that aims to illustrate the appearance of hyperstatic forces.

If we consider that the interfaces, as well as the elements of the human and robotic kinematic chains, are rigid, the twists ${}^{f}T_{g}^{(R)}$ and ${}^{f}T_{g}^{(H)}$ must be equal. Failing in doing so will result in the inability of the system to move. Hence, applying external forces when the twists are different will not initiate motion but instead they will propagate through the system as hyperstatic forces affecting the human limb. In practice, this phenomenon is mitigated by the use of flexible elements in the interfaces, yet it is never completely eliminated.

A formal description can be obtained by analyzing the system through screw theory. According to (2), the sum of the twists should be equal to zero

$${}^{f}T_{g}^{(H)} + {}^{g}T_{f}^{(R)} = 0. \tag{3}$$

If we apply the twist's symmetric property and considering that $\hat{\imath}_x$ represents the unit vector of twist ${}^{f}T_{g}^{(x)}$, we can rewrite (3) as follows:

$$\begin{gathered} {}^{f}T_{g}^{(H)} = -{}^{g}T_{f}^{(R)} = {}^{f}T_{g}^{(R)}, \\ \left|{}^{f}T_{g}^{(H)}\right| \hat{\imath}_h = \left|{}^{f}T_{g}^{(R)}\right| \hat{\imath}_r. \end{gathered} \tag{4}$$

The equation presents two scenarios; in the first, both magnitudes are zero, despite the values of the unit vectors, which can be interpreted as no motion in either chain. The second scenario requires that the unit vectors and the magnitudes of both chains are equal meaning that the chains share the same angular velocity, pitch, and IAR.

It is important to remember that ${}^{f}T_{g}^{(H)}$ and ${}^{f}T_{g}^{(R)}$ are the twists that describe the open human and robotic chains, meaning that theoretically the IARs need to be equal for the closed chain to move. Nevertheless, in exoskeletons, movement can be obtained despite discrepancies between the IARs. This reveals that there is a velocity of a body in relation to itself, which can be expressed as the existence of a third twist:

$${}^{f}T_{g}^{(H)} + {}^{g}T_{f}^{(R)} + {}^{f}T_{f'}^{(R)} = 0. \tag{5}$$

The twist ${}^{f}T_{f'}^{(R)}$ represents the velocity of deformations present in the system. Due to its hyperstatic nature, it is impossible to determine the precise geneses of this twist. The soft tissues surrounding the interfaces (i.e., skin) and in the effective human joint (i.e., meniscus in the knee) are capable of producing the new twist by deforming themselves [28]. Furthermore, the flexible elements are used in the connection between human and exoskeleton, which also contribute to ${}^{f}T_{f'}^{(R)}$. Though deformations in flexible connections do not occur explicitly in the human limb, they can chafe or damage the tissues in contact [29] during prolonged usage.

The manifestation of deformations implies that there are forces generated compressing the human limb rather than helping it move. These forces, known as uncontrollable forces [30], are responsible for compromising both safety and comfort.

It could seem that the solution for this problem is to simply design mechanism so that the IARs are aligned, yet mapping $\hat{\imath}_h$ is not an easy task. It is important to notice that most human articulations act on several planes of the body (sagittal, transverse, and coronal) at the same time as well as having small translations due to bones sliding. The actual location and direction of $\hat{\imath}_h$ depend on the geometry of the articulating surfaces, payload, and health of tissues such as cartilages and ligaments [31].

Clinically, a noninvasive way to estimate the IAR pathway is by taking successive radiographies of the joint of interest, yet it has significant errors [32] as the radiography only obtains a point in a plane rather than a line in space. Predicting the position of $\hat{\imath}_h$ requires a lot of information, especially the description of bones' contact surfaces. These surfaces are very complex and cannot be determined exactly through noninvasive methods. Additionally, biomechanical models of joints, such as [33], usually rely on several calibration parameters to adjust for the variability of dimensions among people. Thus, failing to set these parameters to the correct value for each person will produce an error estimating the position and orientation of $\hat{\imath}_h$.

Taking into account the excessive variance of morphology among subjects and the intrinsic complexity of the human joints, it is impossible to determine a general design that maximizes the performance while minimizing the mechanical interference [26] for every wearer.

Therefore, it is a common practice to simplify the human joint kinematics when designing the robotic joints. Using simple robotic elements such as revolute or spherical joints to model human anatomy only considers the dominant rotations and neglects the small dose of concealed translations [34] making it impossible to correctly comply with the user [35]. Yet the great advantage is the mechanical simplicity obtained, which translates into simpler designs, actuation, control schemes, and (consequently) cheaper prototypes.

3. State of Art

During gait, the whole body is engaged, from toes to arms. Nonetheless, the ankle, knee, and hip have been identified to be more relevant than any other joint, as they perform the major motions and torques. This led pioneer researchers to neglect the motion of the bones in the foot and to treat them like one continuous link, as well as considering the upper body as a concentrated mass, concentrating their efforts in these three joints.

Another common simplification is to only consider the effects of the joints along the sagittal plane (which divides the right side of the body from the left), as these also represent the majority of motion and torque compared to the effects of the joints in the two remaining planes.

Researchers have acknowledged the axial misalignment situation and have been proposing new mechanisms that redefine the paradigms of exoskeletal design. They no longer design structures that facilitate the engineering that is kinematics or control but design them with a human-centered perspective looking for a better adaptation to the user's morphology.

From a physiological perspective, each of these joints has a specific geometry, workspace, function, and characteristic number of elements involved (bones, muscles, and ligaments). As a consequence, we will group the reviewed mechanisms according to the joint they are supporting.

3.1. Ankle. The ankle involves the relative movement among four bones in three joints (Figure 3(a)). The tibia and fibula converge in the tibiofibular joint, which produces almost no motion but serves as a bracket to align the talus. The tibiofibular joint in contact with the talus is known as the talocrural joint; it is responsible for plantar/dorsiflexion (movement on the sagittal plane). And lastly, the joint between talus and calcaneus, called the subtalar joint, is responsible for the remaining movements [36].

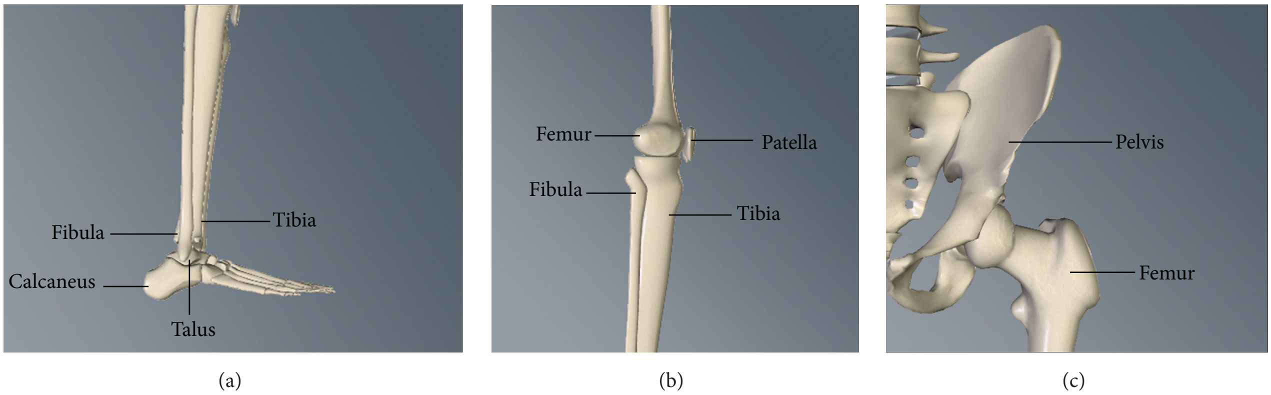

Figure 3: Anatomy of the human joints: (a) ankle, (b) knee, and (c) hips. Powered by BioDigital [66].

The ankle joint registers the greatest torque during gait compared to the hip and knee [37]; this phenomenon is associated with the ankle's distal position along the limb which creates greater lever arms.

As explained before, the focus is on plantar/dorsiflexion as these movements represent the majority of motion during gait. As a consequence, previous designs tend to be just a revolute joint [5, 38–42]. Nonetheless, the torque generated at the human ankle is so large that inconsistent rotation center of the ankle mechanism may be a potential risk against the wearer's safety [43]. Furthermore, balance may be compromised when limiting the motion of the ankle as it depends on its proper functioning [44].

Agrawal et al. [45] proposed an exoskeleton that has an active plantar/dorsiflexion joint combined with a passive eversion/inversion joint. This prototype was one of the first to use an alternative to the oversimplified approach. The results show a good performance with a simple PD controller regardless of being an underactuated mechanism. On the downside, its dimensions and weight (2.5 kg) limit its portability and its applicability, as well as considerably increasing the inertia.

Fan and Yin [46] made a 3-RPS (Rotational-Prismatic-Spherical) parallel mechanism. The design is capable of moving along all of the ankle DOF's while providing a complying couple with the user. The results proved that the ankle joint meets the kinematical and dynamical requirement for rehabilitation, yet its application for a portable exoskeleton is also limited due to its large size.

At the university of Bristol, Carberry et al. [47] used a 2 DOF 2-RP parallel mechanism that allows the same movements as the one of Agrewal. The proposed design is lighter (weighting only .75 kg) and easier at donning and doffing. In addition, the exoskeleton addresses intersubject variability by means of a parametric design, thus making it a more suitable solution for assistive exoskeletons.

Hong et al. [43] proposed a passive spherical five-bar linkage mechanism parallel to an active RSU-chain (Rotational-Spherical-Universal). The design intends to closely locate the axis of rotation of the ankle exoskeleton to that of the wearer's ankle. The results show that the design is capable of reaching the whole spectrum of positions as the human ankle, though they are in early design stages as no prototype has been developed yet.

3.2. Knee. The knee is considered a condyloid joint [48] formed by the femur and tibia (Figure 3(b)). It allows flexion/extension and internal/external rotations; nevertheless, internal/external rotations are severely constrained when the knee is loaded under body weight or fully extended [49]. During flexion/extension, tibia rolls and slides on femur causing the instantaneous axis of rotation to be displaced up to 30 mm [33].

Typically, the knee is simply modeled as a revolute joint, as seen in [40, 41, 50–52]. This approximation simplifies greatly the mechanical and kinematical considerations during exoskeletal design at the expense of ergonomics and mechanical compatibility with the human anatomy. According to [53], this oversimplification produces parasitic forces in the user's knee that may lead to discomfort or injury over prolonged time of use.

To avoid the said problem and provide a better user experience, several researchers are proposing new mechanisms that comply with the users' anatomy. Some of the first designs to do so are those proposed by Wang et al. [53]. They proposed four compliant designs using combinations of simple kinematic element as an alternative of the previous approximation: (1) pin and slider, (2) cam and slider, (3) pin and pinned slider, and (4) cam with pinned slider. They used an anatomically correct commercial model of the knee (A82 Functional Knee Joint Model, 3B Scientific GmbH, Germany) to have a more approximate measure of the internal forces without recurring to invasive instrumentation setups. According to the results obtained, the implementation of an extra joint as a compliant element reduces the magnitude of the forces generated at the knee almost to a tenth.

Parallel to Wang et al.'s work, Ergin and Patoglu [54] developed a self-aligning knee exoskeleton by means of a more complex mechanism. The design was based on a 3-RRP planar parallel mechanism which included 3 DOF, two passive translations in the plane and one active rotation along the perpendicular axis. The reported space where the ICR could exist was a 120 mm diameter circle in the sagittal plane and infinite number of revolutions along the z-axis. However, the dimensions of the prototype are too big, compromising the portability of a complete LLE that implements this design.

A couple of years later, Celebi et al. [49] developed a new self-aligning knee exoskeleton, ASSIST-ON Knee. This design was based on the Schmidt coupling [55], this coupling allows for axial misalignments between its input and output links without losing power in the transmission. The mechanism allowed the same DOF as its predecessor but a smaller diameter (48 mm), which indicates a more compact prototype.

Another proposal for a compliant design was given by Kuan et al. under the name of Adaptive Coupling Joint (ACJ) [56]. The ACJ is based on a 2 DOF five-bar linkage mechanism. It allows an external torque source to be applied in the mechanism while permitting the displacement of the axis of rotation through a set trajectory. According to the authors, the ACJ is being manufactured and prepared for further bench testing.

The presented designs use passive DOFs to be driven by the human limb and couple accordingly; however, this tactic sacrifices the weight support capability of the exoskeleton. This negligence may imply a reduced area of opportunity for further applications. Considering this, and trying to reduce pain for people with knee osteoarthritis, Lee and Wang [57] built a prototype that was capable of providing weight support during the first 20° of flexion and a compliant coupling for the rest of the motion. Unlike previous designs, the approach of this prototype was through deformable links rather than rigid links. The results show that this design was capable of supporting up to 20% of human weight during walking on level floor.

3.3. Hip. The hip joint is a multi-axial ball-and-socket synovial joint where the femur head acts as the ball and the pelvis as the socket (Figure 3(c)). The hip joint moves in different planes that pass through the joint center, behaving as a kind of spherical joint, allowing three DOF's. All these DOF's are important in order to allow stable locomotion, even in a straight line [58]. Considerably, the hip is the least studied joint in terms of proposed designs for compliant exoskeletons.

Singla et al. [59] utilized the ball-and-socket model of the hip and implemented a spherical 3-RRR mechanism. Similar to Hong's ankle mechanism discussed previously, the mechanism tries to locate its own axis of rotation as close as possible to the one of the hip. It is important to notice that this design has a fixed center of rotation with respect to the waist and thigh attachments. Results yield an acceptable mechanism kinematically but dynamic performance was not considered.

Pan et al. [60] proposed a more compliant exoskeleton than Singla et al.'s. The design consisted of a 5-DOF 3-PUU parallel mechanism. Once coupled with the user, two of those DOFs are passive and are used to align with the user's hip, and the remaining are active and are used to control its position. The kinematic analysis suggests that the configuration is reliable; however, there is no prototype yet.

Yu and Liang [61] proposed, similar to Pan et al.'s design, a 6-DOF 3-UPS parallel mechanism. This exoskeleton used 3 DOFs to align the user's hip. The design was optimized using the authors' proposed Manipulability Inclusive Principle, which compares the manipulability ellipsoid [62] of both kinematic chains to ensure the robotic kinematic chain can shadow all human's movements. Using this principle should be proof of its assisting ability and quicker reaction.

3.4. Combined. To our knowledge, there is only one lower limb exoskeleton with more than one active compliant joint: the design of Yang et al. [63] known as Bionic Lower Extremity Rehabilitation Exoskeleton (BLERE). At the knee, they used a pinned slider alongside a cam as proposed in [53], while at the hip, they used a curved slider and two revolute joints allowing free movement in all of the 3 DOFs available. Only the flexion/extension motion is powered in both mechanisms. The prototype proved the compliance of the design yet its big size may be still a problem for massive implementation.

4. Methodologies

All of the works mentioned represent an advancement in the solution of the misalignment problem; nevertheless, each one is focused on a specific case of study. To attend the general problem, a couple of researchers have proposed design methodologies to facilitate the coupling between an exoskeleton and the human user.

The first one was proposed by Jarrassé and Morel [30] after recognizing the hyperstaticity generated when connecting the human and robotic kinematic chains. Its main objective is to prevent the manifestation of uncontrollable forces rather than align the chains. The method, given an exoskeleton designed to replicate a limb kinematic model, provides three equations to design passive mechanisms that act as interfaces between the kinematic chains. These equations derive from the *Global Isostaticity Condition* (GIC), which establishes that no forces are to be transmitted to the human chain through the interfaces and no velocities are allowed in the robot chain when the user is static. This condition is first stated in terms of the spaces of twists and wrenches and then it is expressed in terms of the connectivity of the mechanisms involved (robot, human, and interfaces) so that at the end we can calculate the number of passive DOFs necessary in the interfaces to fulfill the GIC.

The methodology was applied in two experiments with the same exoskeleton, one with a manikin and the other with human users. The results in the first experiment reduced the appearance of uncontrollable forces by an average of 96% while those of the second have a less impressive yet significant reduction of about 30%. Nevertheless, the reduction of uncontrollable forces came at the cost of also reducing the assistive forces meaning a lower efficiency for the robot.

This new approach to exoskeleton design focuses on the interfaces leaving the original robot structure untouched. The direct implication is that any exoskeleton already available could be benefitted by new interfaces without altering its current design, which should not affect their control scheme. On the other hand, its greatest restriction is that the method can only be applied in robots that mimic the human limb anatomy and that have all of their joints powered.

Later on, the *Kinetostatic Compatibility Method* was developed by Cempini et al. [64]. Different from the hyperstaticity approach from the aforementioned method, this one focuses on avoiding the misalignment between chains. The objective is to design *self-aligning mechanisms* (SAM), much more similar to the mechanisms described in the previous section, so that these fulfill four requirements: kinematic closure, adaptability, controllability of the human joint position, and assistance effectivity. Regardless of the specific application of the exoskeletons, the requirements are the same.

Cempini's strategy is to add the necessary degrees of freedom to the kinematic models of the human limbs so that the minimal set of variables that define the pose is covered; that is, when modeling a hip as a spherical joint, the added DOFs are the three remaining translations to cover the six parameters that define 3D space. These extra DOFs are called deviations and are used as an independent parameter that helps define the homogeneous transformations matrices for the human chain.

The expanded model then helps to set the restrictions necessary to achieve all the requirements leaving three elements that can be set by the designer: the desired workspace, the human articulation variability, and the SAM chain itself.

While this method presents a more general solution in terms of the possible robotic kinematic chain to be used, there is no experimental result that would let us quantify its success. It is also important to emphasize that the choice of a suitable kinematic model is out of the scope for this method as it is extremely difficult to generalize.

Lastly, it is highly recommended to revise both of these works to further understand the concepts and the formalization of the individual objectives into mathematical equations.

5. Discussion

The presented lower limb exoskeletons are capable of accepting large misalignments between axes, which allows them to be used by different sized people without the need to manually adjust them. Due to the lack of adequate "in vivo" measurements of human morphology, these exoskeletons represent a solution for the misalignment problem as well as an improvement on the first proposals; however, some disadvantages still need to be addressed.

A great disadvantage of these self-aligning mechanisms is that they all increase design complexity and mechanical impedance compared with exoskeletons based on simplified human articulations. The increased mass is especially critical for machines interacting with human users, since it amplifies the risk of injuries in case of failure [65]. Consequently, it is essential to find the best tradeoff between a theoretically misalignment-free design and a simple mechanism.

Also, most of the designs discussed use passive DOFs to be driven by the motion of the user's leg, thus letting the exoskeleton be self-aligning. These underactuated systems provide torque assistance in the desired joint but lack weight support. This means that the forces generated by the exoskeleton weight, as well as the ones generated by its actuators, will not be translated to ground but to the user. Though it has not yet been proved, the lack of weight support for prolonged time may cause damage or pain in human joint tissues, thus limiting applications for assistive and augmentation purposes where long-time usage is fundamental.

Another perspective is given by Zanotto et al.'s investigation [65]. They compare the effects of the axial misalignment to the inertial effects. Human-robot interactions are sensed by two six-axis sensors mounted at the interfaces while torques exerted by the actuators are measured by means of single-axis sensors. The results suggest that the inertial effects are considerably larger than the ones produced by misalignment, as well as pointing out that the traditional approach may be sufficient to guarantee the wearer's comfort in spite of substantial misalignments. While this study may contradict the purpose of specifically designing mechanism to comply with the axial misalignment, it is important to emphasize that the research does not consider the internal forces that act on the limb; therefore, the conclusions given are purely from the robot point of view.

Finally, it is fundamental to consider that there must exist balance between exoskeleton compliance and inertial effects, since adopting larger, more complex mechanisms can result in an impediment for development and massive distribution of this type of robots.

6. Conclusion

The exoskeleton development has had remarkable progress regarding correct compliance between robot and user. The new human-centered design approach has led to several designs that have successfully attached the robot without any major alignment problems, as well as methodologies that help designers to create robots capable of complying with the human. Yet further studies are needed to ensure the mechanisms' capability of assistance as well as weight support capability of the exoskeleton. Physical prototypes are needed to better understand the capabilities and limitations of each design.

Moreover, there is still a lot of work to be done to achieve Ferris' futuristic vision of exoskeletons. The next step towards achieving ideal mechanical design is to ensure that no forces (caused by weight, inertia, or hyperstaticity) are introduced at any point of the lower limb. We actuate the systems in such a way that the efficiency of the robot and the safety of the user are not compromised and, finally, design complete lower limb exoskeletons to assist every joint during gait.

Competing Interests

The authors declare that they have no competing interests.

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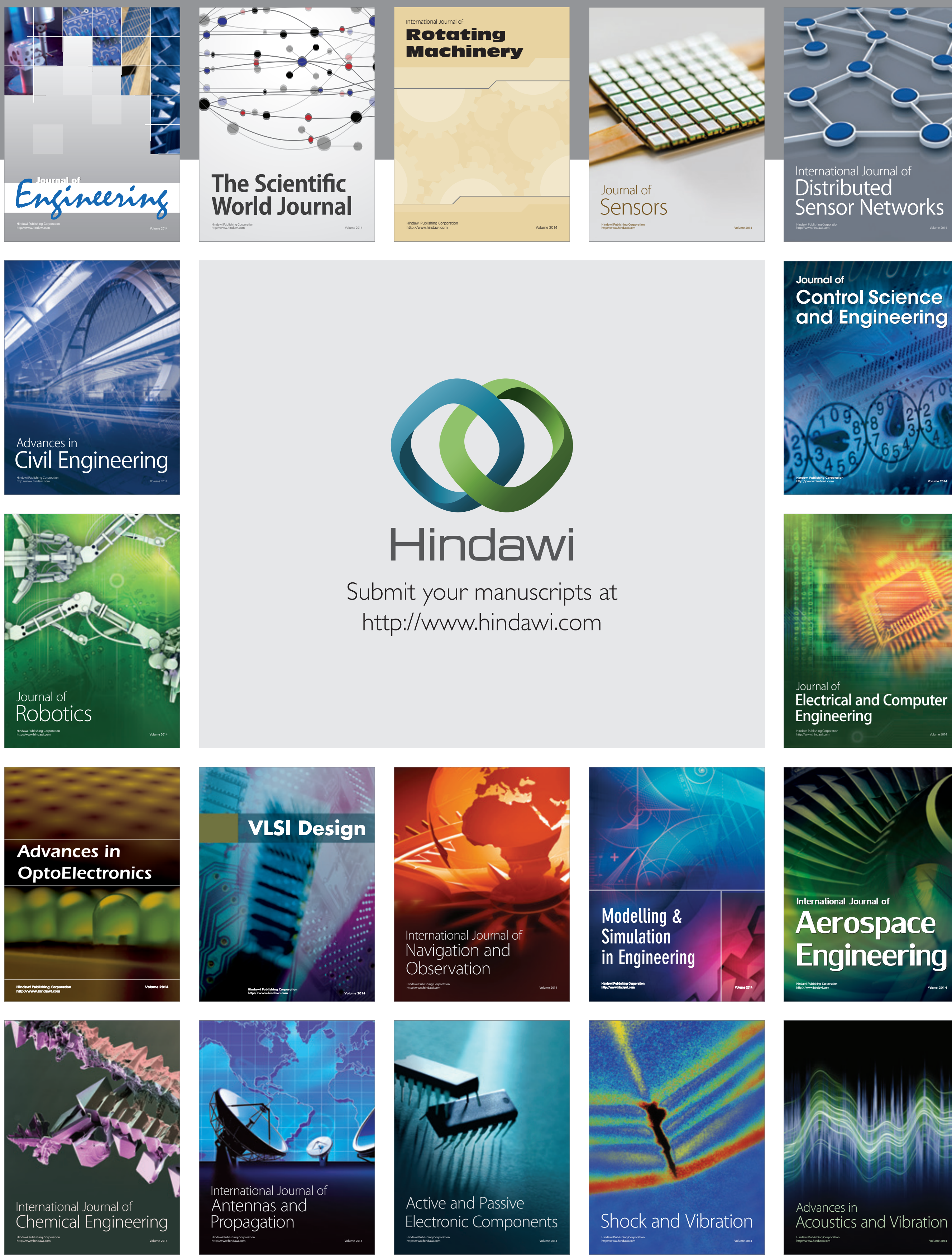
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