Alexandria Engineering Journal (2023) 77, 383–393

HOSTED BY

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Transmission and actuation systems in cable-driven, walking-assistance exosuits based on postural and dynamic synergies

Daniel Rodríguez-Jorge [a], **Francisco Romero-Sánchez** [b], **David Rodríguez Salgado** [c], **Alfonso González González** [c,*]

[a] *Grupo INGELEV, Dpto. de Ingeniería Mecánica, Energética y de los Materiales, Universidad de Extremadura, Spain*
[b] *Grupo DÉDALO, Dpto. de Ingeniería Mecánica, Energética y de los Materiales, Universidad de Extremadura, Spain*
[c] *Grupo Ingeniería de los Procesos de Fabricación, Dpto. de Ingeniería Mecánica, Energética y de los Materiales, Universidad de Extremadura, Spain*

Received 15 November 2022; revised 8 May 2023; accepted 3 July 2023
Available online 7 July 2023

KEYWORDS

Biomechanics;
Exosuits;
Walking assistance;
Cable-driven;
Synergies

Abstract The design of walking-assistance exosuits is becoming increasingly popular among those who aim at developing a light, affordable and wearable system. They are indeed an alternative to traditional exoskeletons, which tend to be bulkier and more expensive. The main advantages of exosuits, as opposed to exoskeletons, are their lower weight and price, as well as their increased wearability and kinematic compatibility with the user. Thus, it is key to optimize their design and, particularly, the number of actuators and the actuation scheme. One of the current, common ways to achieve better designs, is to conduct a Principal Component Analysis (PCA) on some of the involved variables to reduce their dimensionality and thus, simplify the actuation system. The goal of this paper is to analyze the different variables upon which PCA can be conducted and propose the resulting actuation schemes, comparing the results and determining the best design approach for the design of a synergy-based, gait-assistance exosuit. The study focuses on both postural and dynamic synergies to optimize their design. Here, both synergy types are reviewed from a design perspective, yielding different design criteria following a PCA-based study, each with their own set of advantages and disadvantages. Thus, the design of cable-driven exosuits is optimized via analysis of gait parameters related with its actuation, such as joint torque or cable extensions. Kinematics or postural synergies lead to a higher cumulative variance of the first principal component and the transmission system is simpler than the ones obtained through dynamic synergies.

* Corresponding author.
E-mail addresses: danielrj@unex.es (D. Rodríguez-Jorge), fromsan@unex.es (F. Romero-Sánchez), drs@unex.es (D. Rodríguez Salgado), agg@unex.es (A.G. González).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2023.07.004
1110-0168

1. Introduction

Currently, more than 500 million people are affected by some form of gait pathology worldwide [1]. No change in this trend is foreseen in the near future, given the fact, for example, that the European population over 65 years of age could grow by about 30% by 2080 [2]. Lately, numerous solutions have been proposed to improve the mobility of people, with exoskeletons or exosuits standing out among them. The range of applications of exosuits has expanded significantly in the last decade as a natural evolution of the traditional exoskeleton, which offers a rigid solution, limiting the user's mobility to that imposed by the structure of the system. On the other hand, exosuits get rid of such drawbacks in exchange for a lower maximum torque transmitted to the joints. Since exosuits do away with rigid elements, it is the user's own body that assumes the support function, while the cables act as muscle-like actuation units, capable of transmitting forces to the various body segments. The main advantages of these systems are their lower weight and greater comfort for the user, restricting his or her movement to a much lesser extent, unlike rigid exoskeletons [3]. The lack of support structures significantly reduces the weight of the device. For all these reasons, there is an increasing number of exoskeletons under development to promote active ageing. This line of action addresses one of the major challenges at international level, which is health. The promotion of an active and healthy life, especially in old age, involves, in some cases, assisting movement. It is in this context that the aforementioned exosuits, particularly those that assist rather than impose movement for either the upper or lower limbs, become particularly relevant. For example, there are a large number of upper limb support devices, including the arm and hand [4,5], most of which are similar to exosuits with a strong textile component. Some lower limbs exoskeletons are also developed, as in [6,7]. The force to be transmitted, however, becomes their most obvious limitation: they are only able to assist about 30% of the total torque required at each joint. This barrier is due to the way power is transmitted in a cable actuation and the high contact forces between the suit and its wearer. Thus, the major benefit of exosuits is to provide additional support during everyday activities, such as walking, grasping or reaching for objects, or stabilizing gait under pathological conditions, or in the elderly. This article proposes several approaches to a new design criterion based on kinematic and dynamic synergies for cable-actuated gait-assistance exosuits. The methodology is particularized for the lower body, as this is the objective of the project in which this study is framed, although its use can be extended for upper limbs exosuits Kinematic and dynamic synergies are gait-related variables of one type or the other that can be studied from a statistical perspective to, in general, reduce the problem dimensionality. For instance, elevation/segment angles and flexo-extension angles are two postural variables, whereas joint torques and reactions are dynamic quantities. Analyzing synergies related with human motion was approached in [8–14], whether focusing on exoskeleton design or not. Indeed, the use of statistical techniques, such as principal component analysis, to determine the design of a mechanical system as such aiming at a more optimal design is not new, being that examples in closely related applications such as hand assistance. For example, in [15], kinematic or postural synergies were used in robot hands to cooperatively move five fingers with only two actuators, decreasing the weight and price of the final device. The synergies approach was introduced in [16] for a hand assistance device actuated by Bowden cables. This synergy approach is well known and has been used for the last thirty years to simplify the human motion problem and to study the relationships between its various degrees of freedom [17,18]. Since weight and comfort (or "wearability") are determining factors when it comes to assess gait assistance in those with motor pathologies, it is our task to extend the scope of application of principal component analysis, assessing both kinematic and dynamic synergies, to present different approaches to designing the actuating unit of these assistive devices to make them lighter, cheaper and more comfortable. In other words, based on the kinematic and dynamic coordination inherent to the human gait cycle, we will present novel designs to reduce the number of required actuators in exosuits capable of assisting the hip, knee and ankle in both legs. Practical applications can be found for gait support exosuits that are especially lightweight, as in [19], for example, where active rehabilitation is enabled in patients with various pathologies. Another use being explored in lower limb exosuits is the reduction of the user's metabolic cost and the reduction of muscle fatigue. In [20] a lightweight exosuit for hip assistance of only 2.5 kg is presented, reporting a decrease in metabolic cost of up to 8%. There are other similar studies, as in [21,22], all of them addressing the issue of metabolic cost reduction, proving that the weight and comfort of these devices plays a fundamental role when dealing with rehabilitation, gait assistance of improving the capabilities of healthy subjects. Traditionally, one actuator has been used for each degree of freedom to be actuated, although new designs, as in [23], try to reduce their number, since they are the main contributors to the overall system price and weight. The principal component analysis proposed here seeks to highlight how its application to the different variables involved in the performance leads to different design philosophies, as well as which of these variables are most beneficial, emphasizing the notable reduction in dimensionality achieved. A novel approach to the design of exosuits that has already been successfully applied to upper limb assist devices, which seems to be even more justified for use in the lower limb due to the cyclic nature of gait.

2. Methodology

The methodology to be followed to achieve an exosuit for walking assistance with minimum performance can be divided into the following sections. Firstly, the inverse dynamics model followed by the principal component analysis and its relationship with the variables under study, both kinematic and dynamic, is presented. This is done by acquiring the kinematic and anthropometric data from a public data base, plus ground contact force, for a target population of adult subjects, developing a 3D model for the exosuit-user interface and an inverse dynamics model to predict cable displacements and joint torques during gait. Secondly, different design approaches, for both kinematic and dynamic synergies are presented for their application to the design of walking assistance. Finally, the design of the performance scheme based on synergies is analysed.

2.1. Inverse dynamics model

Since studying the gait-related variables and their nature during the gait cycle is the key aspect to the proposed synergy-based analysis, a model that can reliable predict their behavior is a fundamental part of the research. This paper will focus on both kinematic and dynamic synergies, thus it is necessary to fully comprehend the evolution of kinematic variables within gait (both concerning the user of the exosuit, and the exosuit itself) and the dynamic variables, i.e. joint reaction forces and torques. Kinematic data related to the user's movement can be measured via tracking elements or sensors, while for the population under study, they are provided in the public data base in [25]. To obtain the dynamic variables that correspond to such kinematic output, the authors proposed an inverse dynamic model specifically developed for exosuit analysis and design in [26]. Fig. 1 (right) shows a simple scheme used for the lower limb, showing the global and local reference frames, as well as the segment angles and joint torques. Notice that the model is 3D, since the Z axis is shown. Thus, centripetal and Coriolis accelerations will play a role in the dynamic equations. Such equations can be derived once the geometrical model is known (Fig. 1) and the kinematic data is obtained from measuring or a data base, and can be split into the different segments:

- Segment 1, foot.

$$F_{a,i} = m_1(a_{1,i}+g_i)-F_{r,i} \quad i=1,\ 2,\ 3$$

$$n_{a,i} = I_{1,i}\ddot{\theta}_1 - \left(r_{ga,P} \times F_r\right)\big|_i - \left(r_{ga,A} \times F_r\right)\big|_i i = 1,\ 2,\ 3$$

- Segment 2, shank or leg lower segment.

$$F_{k,i} = m_2(a_{2,i}+g_i)+F_{a,i} \quad i=1,\ 2,\ 3$$

$$n_{k,i} = I_{2,i}\ddot{\theta}_2 - \left(r_{gk,k} \times F_k\right)\big|_i + \left(r_{gk,A} \times F_a\right)\big|_i + n_{a,i} i = 1,\ 2,\ 3$$

- Segment 3, thigh or leg upper segment.

$$F_{h,i} = m_3(a_{3,i}+g_i)+F_{k,i} \quad i=1,\ 2,\ 3$$

$$n_{h,i} = I_{3,i}\ddot{\theta}_3 - \left(r_{gh,h} \times F_h\right)\big|_i + \left(r_{gh,k} \times F_k\right)\big|_i + n_{k,i} i = 1,2,3$$

These equations, a total of 18 for each of the translational and rotational DOFs of the system, were introduced by the authors in [26], where a more detailed explanation for each variable is given. This set of equations provides the joint reaction forces and torques, the latter being a key part of the proposed design approaches.

2.2. Principal component analysis

In general, a mechanical device designed to actuate *n* independent degrees of freedom will require an equal number of actuators. Therefore, if one wishes to simplify the system by reducing the number of motors, finding relationships between these degrees of freedom can be a key objective. When it comes to the design of exoskeletons and exosuits, there is a tendency to study statistically some of the variables involved, looking for some trend that will lead to a simplification of the resulting design. One such method is principal component analysis or PCA. PCA is a multivariate statistical technique that generates, in general, for any set of statistical variables of dimension *N*, a new set *n* of principal components PCs that accumulate a decreasing percentage of the variance. Such principal components are linear combinations of the input variables obtained from the eigenvectors of the covariance matrix, as in Eq. (1):

$$Q_{N\times n} = \left(PC_{N\times n^*} e_{n^*\times n}\right)\sqrt{\sigma^2}_{n\times n} + \bar{Q}_{N\times n}\# \tag{1}$$

were Q is the target variable, e are the eigenvector of the covariance matrix and σ stands for the standard deviation. $\bar{Q}$ is the average value for each joint. According to the value of the accumulated variance (VAF), researchers can study only a number n^* of principal components smaller than the number of original variables n. Subsequently, the original variables can be reconstructed from such principal components with a higher degree of fidelity to the original ones the higher n^* is,

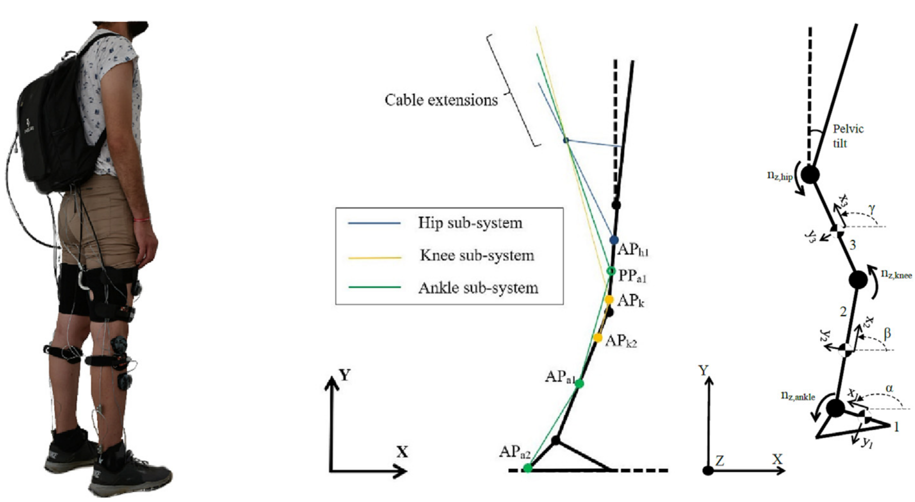

Fig. 1 Left: Scheme of the designed walking-assistance cable-driven exosuit with anchor points placed at the tight and the heel. Center: General model for a multi-joint assistance exosuit. Right: 3D model for the lower limb [27], showing the considered segment elevation angles.

resulting equal in the case that n^* is equal to n. In [17,24], the main objective of principal component analysis is highlighted: to extract the most relevant information from a set of variables, reducing it in size once reconstructed from the chosen PCs. Such variables will be related to the problem whose dimensionality is to be reduced, being in this case those related to human gait, such as joint angles, for example. The minimum number of PCs chosen will ultimately determine the minimum number of actuators, being that n^* can be smaller the greater the accumulated variance of the first principal components. However, the question is: which variables should be studied to find the best exosuit design? Frequently, variables such as joint flexion–extension angles or elevation angles of body segments with respect to a global reference system are selected as study variables, as in [23] for the case of a hand-assistance device. This has generally been yielding good results, allowing researchers to propose actuation system designs capable of actuating a large number of degrees of freedom with few actuators, even with only one. However, certain variables closely related to the exosuit themselves present, in some cases, larger values of the cumulative variance for the first PCs. An example of these variables is the cable extensions, that is, the combined effect of the cable displacements produced by the motors and all elastic deformations involved. For the purpose of this paper, no elastic deformations will be considered, although an approach to their modelling was introduced by the authors in [26]. To delve into them, it is first necessary to describe the type of exosuit to be studied.

2.3. Application to a walking-assistance exosuit

Instead of the variables that have been classically used in the analysis of human gait, joint and elevation angles (the first referring to those shown in Fig. 1, or with respect to a vertical reference, the latter to the relative angles between segments), this article will emphasize two variables closely related to the exoskeleton itself, one of kinematic nature, the other dynamic: the extensions of the cables and the torques exerted on the joints by the exoskeleton during the gait cycle (Fig. 1, left). To be able to evaluate these variables, it is necessary to propose a specific design of exoskeleton, from which their values can be obtained for a specific series of individuals. Thus, a general performance scheme for hip, knee and ankle support shells may be depicted as (Fig. 1, center).

The exosuit in Fig. 1 (right) shows a scheme of the lower limb, which is actuated at its three joints through three cable subsystems, which depart from a backpack (actuation unit) to the so-called anchor points around the joints. Thus, regardless of the number of actuators in the actuation unit, it is possible, knowing the gait of a set of subjects, to determine what will be the instantaneous extension of the cables, as well as the force required on each one to provide at the joint a certain fraction of the required torque. If there is only one actuator, three cables will provide all the required actuation, while in the case of multiple actuators, their actuation will be combined, for instance, as in Fig. 2 for the case of kinematic synergies, cable extensions still referring to the three final cables shown in Fig. 1 (center). In this paper, we present the results obtained for the gait of ten adult male and female subjects whose gait data were published in [25], more specifically subjects 27, 28, 29, 31, 33, 34, 35, 37, 41 and 42. Ref. [25] is a public dataset including mainly kinematic data for healthy adults walking over a treadmill and overground, the latter being more interesting for this practical application. The kinematic data were obtained experimentally using a 3D motion capture system including 12 cameras and force plates for the ground contact forces. Kinematic data were acquired at 150 Hz, while ground contact forces were measured at 300 Hz. Those subjects belong to the target population of a possible walking-assistance exosuit, that is, older adults who may need support to fulfill their daily activities. Those subjects were also partially selected given the homogeneity in their recorded data. Their anthropometric data, as well as various gait parameters such as joint torques and extensions and forces on the cables were determined in [26]. In addition, a methodology for the design of a specific exosuit based on kinematic synergies was introduced in [27]. The novelty of the present work lies in the comparison between the designs resulting from studying kinematic variables (cable extensions) and dynamic variables (torques produced by the exosuit). The analysis and assessment of both design criteria may play a key role in for the construction of this type of exosuit in terms construction, energy requirements or control. For this purpose, it will be necessary to develop Eq. (1) for each case. For the kinematic case (exosuit induced joint angles), and relating cable extensions with radius and pulley rotation, the following equation may be derived:

$$\sum_{k=1}^{n^*} \Delta l_{ijk} = \sum_{k=1}^{n^*} \theta_{ik} r_{jk} = \sum_{k=1}^{n^*} \left(PC_{ik} e_{kj} \sqrt{\sigma^2}_{jj} + \frac{\bar{Q}_{jj}}{n^*} \right) \# \qquad (2)$$

In Eq. (2), the subscripts i, j, and k represent the instant, joint, and actuator, respectively. The term l represents the cable length and θ the pulley rotation, whereas r refers to the pulley radii. To arrive at (2), it was sufficient to substitute the input variable, Q, in Eq. (1) for the instantaneous extensions of the cables. A more detailed derivation of Eq. (1) is found in [27]. Cable extensions can be predicted from the 3D exosuit model in Fig. 1 (center) for a determined subject anthropometric characteristics, exosuit design and gait parameters. Following a similar process, the equation corresponding to dynamic synergies (exosuit induced joint torques) is reached:

$$\sum_{k=1}^{n^*} f_{ijk} \rho_{ij} = \sum_{k=1}^{n^*} \gamma_{ijk} = \sum_{k=1}^{n^*} \left(PC_{ik} e_{kj} \sqrt{\sigma^2}_{jj} + \frac{\bar{Q}_{jj}}{n^*} \right) \# \qquad (3)$$

In this case, f corresponds to the force on the cable, ρ radius of gyration and γ torque exerted on the joint. In this case, Q will stand for the net joint torques on the hip, knee, and ankle throughout the gait cycle for both legs, being that the percentage of torque to actuate will be referred to as $C_{\%}$ and it will stay at around 30%. It should be noted that, in this case, the statistical variables e and σ (standard deviation) will be different from those indicated in (2), since in that case the variable under study was different. Knowing the desired torque assistance at each joint, the inverse kinematic model in Section 2.1 will provide the biological torques during gait, while, considering the exosuit design and for each subject keeping in mind Fig. 1 (center), cable forces can be easily obtained. Note that such forces will be zero at any time the actuation would result in the corresponding cable being submitted to compression.

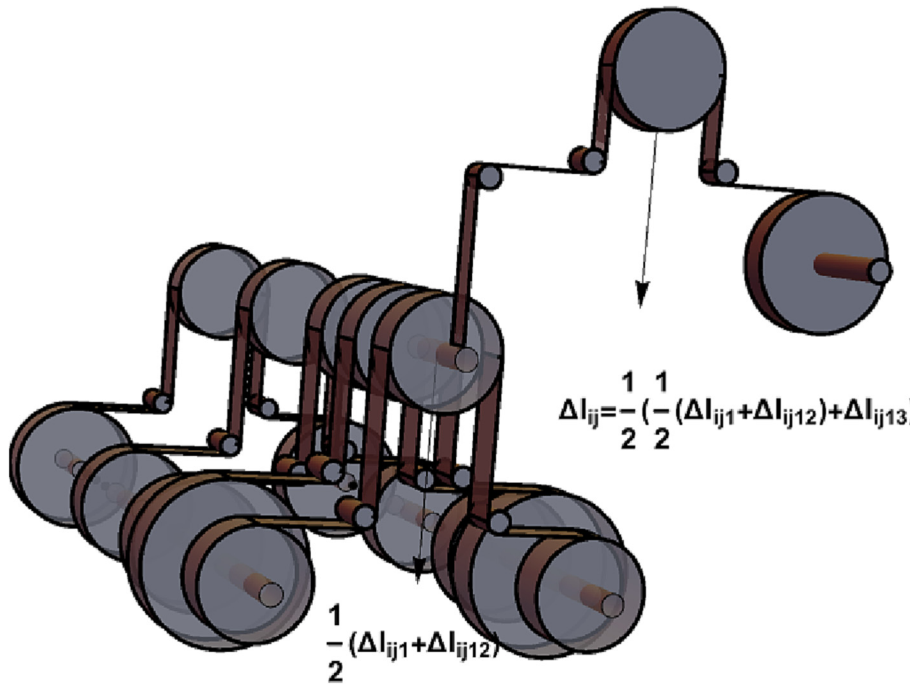

Fig. 2 Scheme of the actuation system for an exosuit based on cable extension synergies, proposed by the authors in [27].

2.4. Actuation approach

When considering the design of the actuation scheme in each case, Eq. (2) will give the expressions of the pulley radii and their rotational control during the gait cycle, while Eq. (3) will give the pulley radii and the evolution of the torque of each actuator along the gait. Now, note that the extension Δl_{ijk} denotes the change in length at instant *i* of the cable that, coming from actuator *k*, contributes to the motion of the cable acting joint *j*. Therefore, and in any case except that of a single actuator $n^* = 1$, the elongation of the cable corresponding to joint *j*, those shown in Fig. 1 (right), will be a combination of the cables coming from each actuator and which, in general, will depend on the design of the transmission system. In [27] a solution for combining the extensions of these cables was presented consisting of combining as many pulley trains as the number of actuators minus one. Fig. 2 shows a scheme of such a system for a general case. In the case depicted, there exist three actuators, while the transmission system manages to combine the output for the three of them (each would actuate following its corresponding Principal Component) in a final pulley, its output being Δl_{ij}. The proposed active mechanism, while allowing to combine the contributions to cable extensions of each actuator, becomes mechanically quite complex when the required number of actuators is high, that being its main drawback. However, as will be presented in the following section, the required number of motors for postural synergies in the target population is luckily very low. The general expression of the cable extensions as a combination of those of each actuator can be found also in [27] which is a linear combination of the partial extensions. In Fig. 2, a general actuation system scheme is presented, being that the number of coplanar subsystems is equal to the number of actuators minus one, and the number of parallel subsystems is equal to the number of joints to be actuated. However, it is worth noting the following fact: although the instantaneous rotation of the different pulleys may be different and therefore dependent on *j* (since each one has a different "winding" of the cable), the "increment of rotation" of all those that are anchored to the axis of the same actuator must be the same. This boundary condition is equivalent to affirming that the derivative with respect to *j* of the rotation of the pulleys is null and, therefore, the "rotation increment" of all those that are anchored to the same actuator shaft must be equal:

$$r_{jk} = C \cdot e_{kj} \cdot \sqrt{\sigma^2}_{jj} \# \tag{4}$$

That is, the pulley radii are proportional to the eigenvectors of the covariance matrix of the extensions in the cables. In general, they are thus dependent on the position of the anchor points and the actuation system in the exosuits themselves.27. A similar path can be followed for the case of joint pair synergies. Knowing the relationship between the forces on the cables and the torque on the shaft, Eq. (3) can be rewritten as:

$$\tau_{ijk} = \left(PC_{ik} e_{kj} \sqrt{\sigma^2}_{jj} + \frac{\bar{Q}_{jj}}{n^*} \right) C_{j\%} \cdot ii_k \cdot \frac{r_{jk}}{\rho_{ij}} \# \tag{5}$$

where τ_{ijk} is the torque curve of actuator *k*. Briefly, it is apparent how a single actuator cannot have more than one torque curve and, therefore, the derivative with respect to *j* of Eq. (5) has to be zero. If the summand including the average values of the joint torques $\bar{Q}_{jj}$ is eliminated, the following expression for the pulley radii is obtained:

$$r_{ijk} = \frac{C \cdot \rho_{ij}}{C_{j\%} \cdot e_{kj} \cdot \sqrt{\sigma^2}_{jj}} \# \tag{6}$$

here the possibility of acting different fractions of joint torque for each joint has been left open. Eq. (6) presents two particularities compared to (4). The first is that the radius of the pulleys depends on i, i.e., on the instant, so that the pulleys must have variable radius, or another element such as cams should be used in the transmission system. The second difference is that (6) guarantees that the change in torque of each actuator is independent of the joints, but not its absolute value. One solution to this problem is to take the smaller of the resulting torque curves as a reference and add constant torques to the remaining joints, adding the additional torque needed to reach the assistance target.

3. Results

Having established the target variables for the application of the PCA and the population on which the study will be carried out, it remains to propose the specific design of the exosuit with which the tests will be performed. This is the same as the one introduced in [26] and consists of two actuators to assist the hip and ankle, with the characteristics shown in Table 1, where t_i is the percentage of the length of each segment where the corresponding step or anchor point is located (see Fig. 1). Furthermore, it should be noted that, while cable extensions are, for the case of infinite cable stiffness, a purely kinematic problem, the torques applied on the joints entail a greater difficulty: where the sign indicates, the corresponding cable will be subjected to compression instead of tension and, therefore, will not be able to exert any torque on the joint. Therefore, the data obtained for the joint torque should be modified, eliminating the gait phases where some cables might be under compression, that is, the sign of the tensile forces must be coincidental when actuating all three joints simultaneously, and avoid compression. There are works that study in detail the determination of the acting phases of an exosuit, as in [28], although here it will be sufficient to avoid that no cable enters compression at the same time that others act. It should also be noted that different results will be obtained for different positions of the anchor points.

It is then sufficient to obtain the results for the joint torques (inverse dynamics model) and the extensions in the cables (exosuit's geometry and gait parameters, taking into consideration the backpack's dimensions and the location of the anchor points, as in Table 1) to apply the principal component analysis. This will yield, on the one hand, the variance accumulated by the different principal components in each case and, on the other hand, the pulley radii defined by expressions (4) and (6). The gearbox ratio in Table 1 will also provide, together with Eq. (5), the torque vurve for each actuator.

Table 1 General characteristics of the proposed walking-assistance exosuit.

	Motor 1	Motor 2
Power [W]	200	200
Max. Speed [rpm]	10,000	10,000
Max. continuous torque [Nm]	4	4
Max. continuous torque at the motor shaft [mNm]	95.6	95.6
Gearbox ratio [–]	1:33	1:79
t1 [%]	0	0
t2 [%]	60	80
t3 [%]	–	30
Back-pack's width [m]	0,32	0,32

3.1. Postural synergies

This case is particularly straightforward as it is a purely kinematic problem, although it is clear that the position of the anchor and/or crossing points may have some impact on the results. Thus, and for the exosuit in Table 1 and the selected population, the following results are obtained for the cumulative variance in synergies of cable extensions (see Fig. 3).

The results show a differential fact: the cumulative variance for the first principal component is around 95%, resulting in the possibility to actuate the exosuit kinematics with a single actuator, and the standard deviation among the ten subjects is low, that is, there is not much deviation between subjects in the studied case. As indicated above, this result could vary for anchor point positions different from those in Table 1. To test this, a parametric study was performed on one of the subjects in the population, by placing the thigh anchor point at ten different positions from hip to knee at 10% intervals of the segment length. The results for the cumulative variance are shown in Fig. 4.

In Fig. 4, the standard deviation between the ten anchor point positions has been multiplied by ten for illustrative purposes, the conclusion being that the position of the anchor points should not have a significant impact on the conclusions drawn here. This result allows the actuation of both legs with a single actuator, even when hip, knee and ankle actuation is required. Moreover, the result is particularly interesting for its great simplicity: the pulleys have constant radii throughout the gait cycle (i.e., they are circular) and the condition of equal rotation on the axis is satisfied in all cases to give rise to the Eq. (4). This will not necessarily be so straightforward when dynamic synergies are addressed in the next section. Eq. (1), applied to the selected population, yields the corresponding pulley set.

In general, the total size of the pulleys is not relevant, since it can be adapted to the designer's needs following Eq. (4) and using C as a way to do so. The relative size of the three pulleys corresponding to each subject is interesting and depends on the subject's anthropometric data, gait parameters and the location of the anchor points. Results slightly vary from one leg to the other for each subject. Only with one set of three pulleys, all six joints might be actuated by the exosuit. If more motors were required, a system equivalent to the one shown in Fig. 2 might be necessary.

3.2. Dynamic synergies

This case, as mentioned above, is more complex than the previous one. Regardless of this, let us look at the results in terms of accumulated variance that the study yields on the target population. We start from the fact that, since the joint torque to be studied (the torque exerted by the exoskeleton on each joint expressed as a percentage of the biological torque) is independent of the exoskeleton, the results will depend to a lesser extent on the position of the anchor points. Another aspect to be taken into account is the actuation phase. Although it would be possible to act as in the case of kinematic synergies and include the complete gait cycle in the study, this would

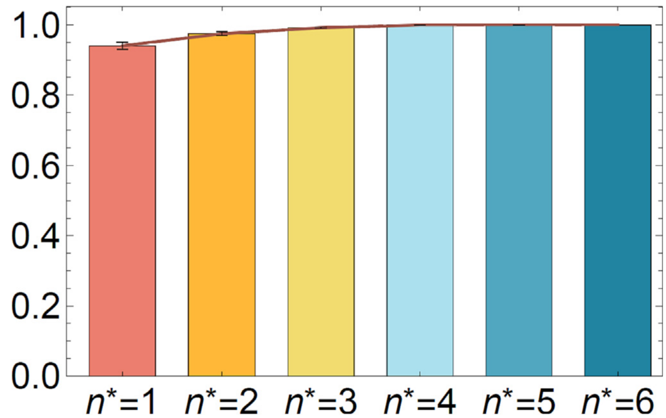

Fig. 3 Cumulative variance for hip, knee and ankle at both legs for the selected population. Postural synergies (cable extensions).

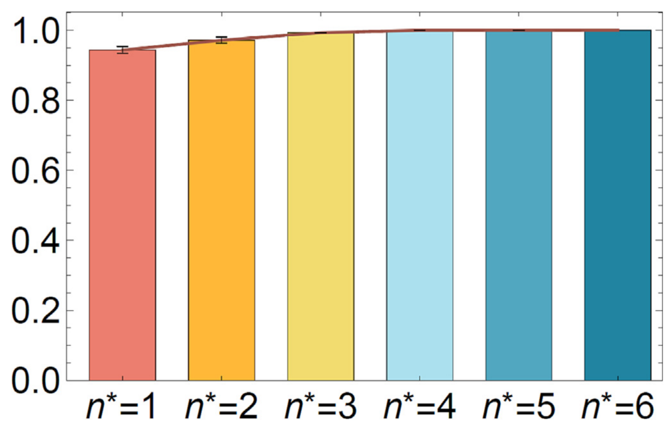

Fig. 4 Cumulative variance for hip, knee and ankle at both legs for one subject, changing the position of the anchor point at the thigh. Postural synergies (cable extensions). Standard deviation $\times$ 10.

not correctly represent the functioning of the exosuits. This is due to the complications of simultaneously acting two joints that demand a torque of opposite sign. For the purpose of this paper, it was chosen to limit the actuation interval to that in which the signs of the three joint torques of each leg coincide. Subject 41 was excluded from the analysis because it had a null performance interval. Thus, the cumulative variances in Fig. 5 are obtained.

In this case, the cumulative variance of the first PC is around 50%, and the result obtained for kinematic synergies is not reached until the third principal component. That is, to replicate the gait cycle in a similar way to how it was done with synergies of cable extensions with a single actuator, three actuators would be required here. This is in addition to the fact that the pulleys have to have variable radii according to Eq. (6), plus the standard deviation is this case, notably higher

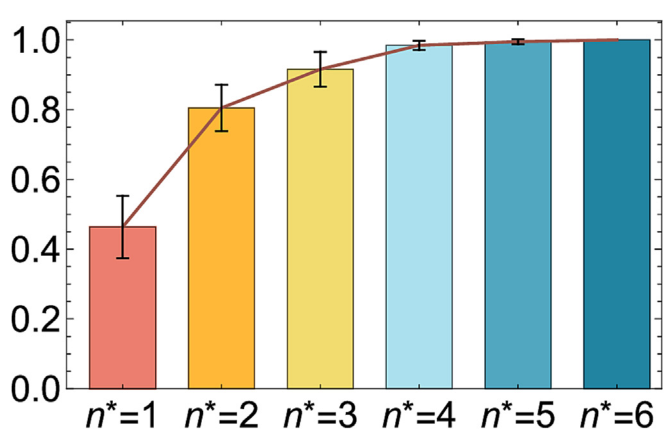

Fig. 5 Cumulative variance for hip, knee and ankle at both legs for the selected population. Dynamic synergies (exosuit joint torques).

than the previous one, resulting in a higher variability of the results for different individuals in the target population. Now there is, however, an advantage in focusing on dynamic synergies: the transmission system design to combine the contribution of all actuators may be far simpler than the one proposed for postural synergies and shown in Fig. 2. Since only torques must be combined, simply joining each cable coming from each motor (each of them corresponding to the torque curve derived from its PC, Eq. (5) may be enough. Fig. 6 shows the resulting "pulleys", which in this case are actually cams. According to Eq. (6), and for one of the subjects (28) of the selected population, the cams profiles may be obtained (see Fig. 6).

Fig. 6 shows how, when focusing on joint torques to perform the PCA, not only is the VAF lower, thus more actuators are required, but also is the transmission system more complex: time-dependent radii means that no normal pulleys can be used, rather cams are needed. However, combining torques from different actuators is simpler than combining extensions, yielding a somewhat feasible solution: cables from each motor are joined and then driven to the target joint. The total assisted torque is also less manageable, since only one joint will find its initial target fulfilled, while the other two in each leg will see a higher or lower value depending on which was taken as a reference, as discussed above. Fig. 6 shows the result of obtaining the cam profiles according to Eq. (6). Please notice that in (6), there exists a constant value C, which applies to all cams in the system, thus being just a measurement of their absolute size. That is the reason why there are no measurements in Fig. 6: while the relationship between radii of different cams is fixed and given by Eq. (6), their total size can be specified by the designer, following their specific needs (smaller cams might be easier to locate in the actuation unit, but bigger ones will require lower torque from the motor). Fig. 7 shows a scheme for the 3D actuation system using only one actuator, thus having a set of three cams per leg, all of which are driven by such motor.

The actuation unit in Fig. 7 shows how the authors decided to decouple both legs from each other, as well as the knee joint, thus enabling them to increase the actuation phase due to limitations such as the maximum clutch torque, the sign of the torque to ensure cables do not actuate under compression and the non-symmetrical nature of human gait. The chosen components for the actuation unit shown in Fig. 7 correspond to a specific set of actuation requirements (providing around 30% of joint torque to the hip and knee and 15% to the ankle). Higher actuation targets might require a more powerful motor, stronger structural and support elements, etc. The difference between cam profiles corresponding to each joint may be very noticeable, something that could add difficulties when it comes to actually manufacturing, assembling and operating the exosuit. This difficulty is, in general, not present in the postural synergy-based approach, that being one of the disadvantages of using the dynamics synergy-based one. Fig. 7 shows both a CAD version of the proposed transmission system (left) and a physical prototype (right), where we managed to use 3–4 cm cams, by limiting the actuation phases. Usually, the dimensions will deppend on the smallest cam, since the minimum radius may limit the cable section, the manufacturing method, etc. The proposed mechanism is specifically designed to allow both postural and dynamic, synergy-based devices, and includes several elements, like clutches, gears, feeders for the cables, etc. In the proposed mechanism, one single motor actuates all three joints for both legs, while the gear ratios selected for the different transmission stages allow the target joint torque to be achieved. The weight of the actuation system ranges between 4.5 and 5 kg depending on the type of transmission used, being a light and compact system compared to other similar devices [30].

Now, as Figs. 4 and 5 show, while postural synergies achieve a high VAF for just the first PC, a dynamic synergies approach will require at between two and three motors to achieve over 80% cumulative variance. This fact is clearly seen when comparing the resulting cable extensions and joint torques exerted by the exosuit during gait when those predicted by the model. Fig. 8 shows both the predicted cable extensions and the ones achieved by one motor using the postural synergy-based approach, and the predicted joint torques applied by the exosuit next to those that would be provided following the dynamic synergy-based approach with three motors.

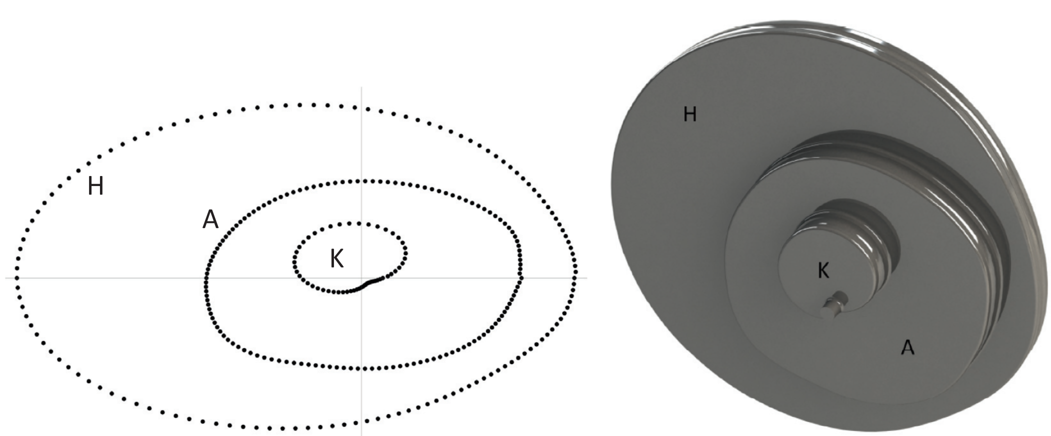

Fig. 6 Cams required to actuate hip, knee and ankle following a dynamic, synergy-based approach during support gait phase (left) and CAD model (right, [29]).

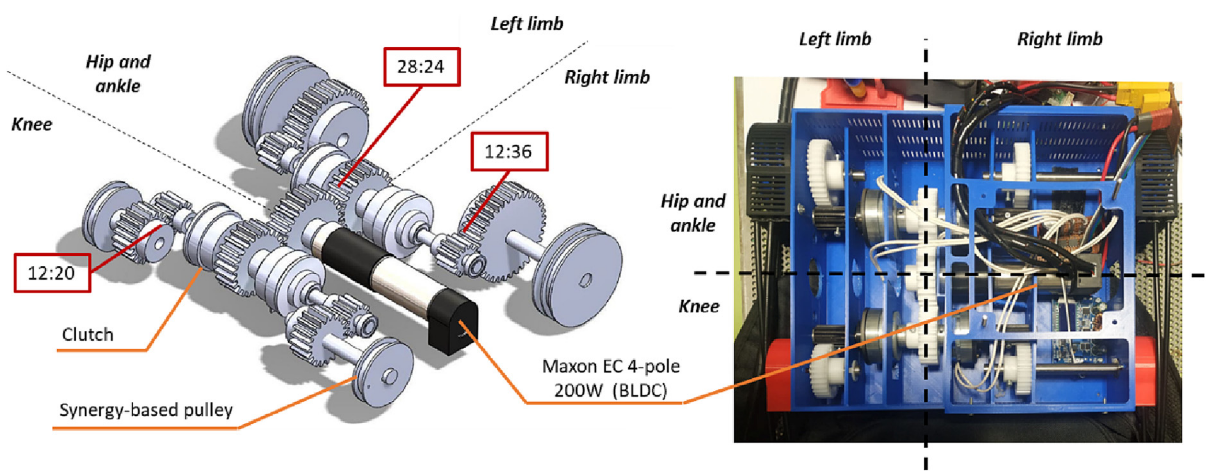

Fig. 7 Scheme of the actuation system for an exosuit based on joint torque synergies. CAD (left) and physical prototype (right).

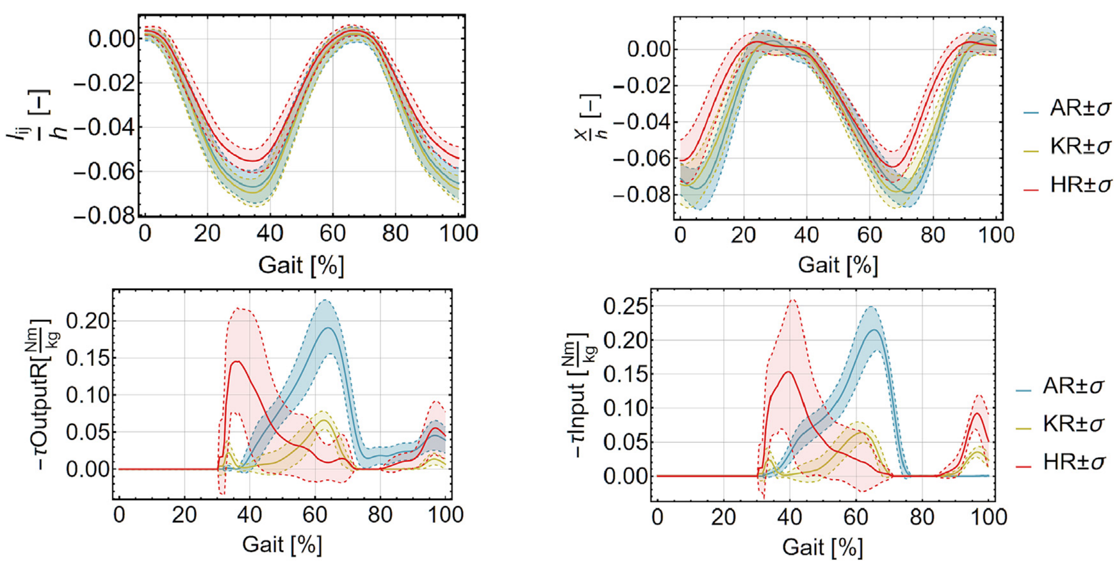

Fig. 8 Predicted normalized cable extensions (X/h) and torques (τ/m) applied by the exosuit on each joint (right) for ankle AR, knee KR and hip HR, and obtained cables extensions l_{ij} with one motor and joint torques with three motors (left). Results are shown for the selected population and only for the right leg. The average value is shown with solid line, and dash lines represent the standard deviation.

4. Discussion

Using cable extensions as a target variable for PCA led to a simple, light transmission system including only one actuator, while remaining able to actuate all three joints, theoretically at both legs. The high value of cumulative variance in the first PC, combined with a simple expression derived for the pulley radii, Eq. (4), resulted in a pulley set each subject in ~~for~~ the selected population. Slight differences are found between the right and left legs for each subject. This effect might be more visible in subjects with motion-related pathologies. Furthermore, the device's adaptability might be greatly increased by using an average set of pulleys instead of those strictly derived from each subject: this may lead to lower accuracy in the actuation but would make the exosuit wearable for many users without changing its design significantly, if at all. On the other side, a completely different design proposal was reached when focusing on dynamic synergies, in this case, joint torques exerted by the exosuit to supply a certain percentage of total torque. While the cumulative variance was significantly lower for the first and second principal components, which may force designers to use two or even three actuators, the overall transmission system proposed for this case (Fig. 7) was much simpler, since combining cables forces is as simple as joining all cables that lead to the same joint. Additionally, whereas in the design proposed for cable extensions synergies all boundary conditions were met, this was not the case for dynamic synergies. This implies that, in the latter case, the joint torque assistance goal will in general not be met, some joints enjoying only a fraction of the total desired torque. This is due to the fact that only the variation of torque is equal for all joints and each motor, while the total value may not coincide. This limitation might be solved by adding any kind of system that provides a constant torque to those other joints, or simply by choosing the joint demanding the most torque (or the least, depending on the actuation system power, actuation phases, etc.).

In general, results seem to indicate that cable extension synergies are the way to go when designing synergy-based exosuits for walking assistance, as opposed to dynamic synergies. Also, selecting variables related to gait, but also related to the suit's actuation may be very convenient, since motor control schemes and even expressions for pulley/cam radii can be derived, directly impacting the exosuit's design. However, there are still other options, such as the radii of gyration, elevation or joint angles (in the sagittal plane or otherwise) in the postural/kinematic category, or the cable forces in the dynamic one, that may be interesting to analyze and compare with the results proposed here. Also, while it is, in theory, possible to actuate all three joints in the lower limb with the number of actuators that, in each case, yields the conducted PCA study, such achievement might not be possible in all actuation systems: the total available power or maximum axes or clutch torques, among others, may be limiting factors. Those may force the designers to select specific gait phases where the actuation must occur, while the exosuit remains inactive in others. This may change the resulting design. For instance, this approach was partially followed here when presenting the results for the cams in Fig. 6: they were assumed to be providing actuation during the support phase only. A clutch system ensures to keep them detached during the swing phase. This may even be done for each joint separately: defining different actuation phases for each joint, provided they are physically independent from one another, will lead to different transmission system designs and may allow the user to enjoy assistance for a longer portion of their gait cycle. Additionally, making the actuation of all joints to be made by a reduced number of actuators may complicate the design of appropriate admittance control schemes and strategies to ensure the correct behavior of the exosuit during its use. This complexity must be addressed and analysed, since it might be crucial to make the synergy-based approach a reality.

5. Conclusions

This work has addressed the comparative study of two types of synergies, kinematic and dynamic, for the design of a gait-assist exosuit, with the ultimate goal of optimizing its design. More specifically, the study variables chosen were, on the one hand, the extensions of the cables of a prototype exosuit during the gait cycle and, on the other hand, the torques produced by the exosuit on the joints. In each case, the design characteristics and boundary conditions to be met were established, highlighting the need to reduce the number of actuators as much as possible in order to reduce the weight and price of the system, as well as to improve its wearability. A key factor in this regard is the cumulative variance of the first principal components of the PCA analysis, being that the higher they are, in general, the lower the number of actuators required to replicate the gait cycle with certain fidelity. The results were evaluated by studying the gait of ten adult subjects through an inverse dynamic analysis. Thus, different results were obtained between the two options, being much higher in kinematic synergies than in dynamic synergies, as well as resulting in a simpler set of pulleys. In addition, the results showed less dispersion in the kinematic analysis than in the dynamic analysis. However, the overall transmission system proposed to combine the actuation of the joint torques produced by the assistive device is simple. In general, and based on the results shown in this paper, using cable extension synergies is recommended over joint torques: it may lead to a lighter, cheaper and more comfortable exosuit, those being their key advantages over traditional exoskeletons.

Funding

This work has been funded by the Ministry of Science and Innovation - State Research Agency (MCIN/AEI/ https://doi.org/10.13039/501100011033) through project PID2019-107491RBI00 and by Consejería de Economía, Ciencia y Agenda Digital, Junta de Extremadura through project GR21098.

Data availability

Raw data were generated at [25]. All data from that study are available at Figshare (https://doi.org/10.6084/m9.figshare.5722711). Derived data supporting the findings of this study are available from the corresponding author (D.R.J.) on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] E. Rocon, A.F. Ruiz, R. Raya, A. Schiele, J.L. Pons, J.M. Belda-Lois, R. Poveda, M.J. Vivas, J.C. Moreno, Human–robot physical interaction, Rev. Wearable Robots, J.L. Pons (Ed.). 2008. doi: https://doi.org/10.1002/9780470987667.ch5.

[2] C. Di Natali et al., Design and evaluation of a soft assistive lower limb exoskeleton, Robotica 37(12) (2014). doi:10.1017/S0263574719000067.

[3] B. Quinlivan, A. Asbeck, D. Wagner, T. Ranzani, S. Russo, C. Walsh, Force transfer characterization of a soft exosuit for gait assistance, Robotica 37(12) (2015). doi: https://doi.org/10.1115/DETC2015-47871.

[4] L. Cappello, D.K. Binh, S.-C. Yen, L. Masia, Design and preliminary characterization of a soft wearable exoskeleton for upper limb, in: 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), 2016, https://doi.org/10.1109/BIOROB.2016.7523695.

[5] M. Xiloyannis, L. Cappello, K.D. Binh, C.W. Antuvan, L. Masia, Preliminary design and control of a soft exosuit for assisting elbow movements and hand grasping in activities of daily living, J. Rehabil. Assis. Technol. Eng. (2017), https://doi.org/10.1177/2055668316680315.

[6] A.T. Asbeck, K. Schmidt, C.J. Walsh, Soft exosuit for hip assistance, Rob. Auton. Syst. 73 (2015), https://doi.org/10.1016/j.robot.2014.09.025.

[7] Y. Lee et al., Biomechanical design of a novel flexible exoskeleton for lower extremities, IEEE/ASME Trans. Mech. 22(5) (2017). doi: https://doi.org/10.1016/j.robot.2014.09.025.

[8] Barroso et al., Shared muscle synergies in human walking and cycling, J. Neurophysiol. 112 (2014).

[9] Liu et al, Postural synergy based design of exoskeleton robot replicating human arm reaching movements, Rob. Auton. Syst. 99 (2018), https://doi.org/10.1016/j.robot.2017.10.003.
[10] I. Grinyagin, E. Biryukova, M.A. Maier, Kinematic and dynamic synergies of human precision-grip movements, J. Neurophysiol. 94 (2005), https://doi.org/10.1152/jn.01310.2004.
[11] P. Neilson, M. Neilson, On theory of motor synergies, Hum. Mov. Sci. 29 (2010), https://doi.org/10.1016/j.humov.2009.10.005.
[12] Esmaeili et al, There is a time shift between muscle synergies and kinematic synergies during normal gait, Gait Posture 81 (2020), https://doi.org/10.1016/j.gaitpost.2020.07.075.
[13] L. Latash, Stages in learning motor synergies: a view based on the equilibrium-point hypothesis, Human Move. Sci. 29 (2010). doi: 10.1016/j.humov.2009.11.002.
[14] Cui et al, Synergies in the ground reaction forces and moments during double support in curb negotiation in young and older adults, J. Biomech. 106 (2020), https://doi.org/10.1016/j.jbiomech.2020.109837.
[15] C.Y. Brown, H.H. Asada, Inter-finger coordination and postural synergies in robot hands via mechanical implementation of principal components analysis, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007, https://doi.org/10.1109/IROS.2007.4399547.
[16] M. Xiloyannis, L. Cappello, D.B. Khanh, S.-C. Yen, L. Masia, Modelling and design of a synergy-based actuator for a tendon-driven soft robotic glove, in: 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), 2016, https://doi.org/10.1109/BIOROB.2016.7523796.
[17] I.T. Jolliffe, C. Jorge, Principal component analysis: a review and recent developments, Phil. Trans. R. Soc. (2016), https://doi.org/10.1098/rsta.2015.0202.
[18] H. Bo, X. Caihua, C. Wenbin, L. Jiejunyi, S. Bai-Yang, G. Xuan, Common kinematic synergies of various human locomotor behaviours, R. Soc. Open Sci. (2021), https://doi.org/10.1098/rsos.210161.
[19] F.L. Haufe, K. Schmidt, J.E. Duarte, et al, Activity-based training with the Myosuit: a safety and feasibility study across diverse gait disorders, J. Neuro Eng. Rehabil. 17 (2020) 135, https://doi.org/10.1186/s12984-020-00765-4.
[20] L. Chen, C. Chen, Z. Wang, X. Ye, Y. Liu, X. Wu, A novel lightweight wearable soft exosuit for reducing the metabolic rate and muscle fatigue, Biosensors 11 (7) (2021) 215, https://doi.org/10.3390/bios11070215.
[21] W. Cao, C. Chen, H. Hu, K. Fang, X. Wu, Effect of hip assistance modes on metabolic cost of walking with a soft exoskeleton, IEEE Trans. Autom. Sci. Eng. 18 (2) (2021) 426–436, https://doi.org/10.1109/TASE.2020.3027748.
[22] F.A. Panizzolo, I. Galiana, A.T. Asbeck, et al, A biologically-inspired multi-joint soft exosuit that can reduce the energy cost of loaded walking, J. Neuro Eng. Rehabil. 13 (2016) 43, https://doi.org/10.1186/s12984-016-0150-9.
[23] E. Tricomi et al, Underactuated soft hip exosuit based on adaptive oscillators to assist human locomotion, IEEE Rob. Autom. Lett. 7 (2) (2022) 936–943, https://doi.org/10.1109/LRA.2021.3136240.
[24] H. Abdi, L.J. Williams, Principal component analysis, WIREs Comp Stat 2 (2010) 433–459, https://doi.org/10.1002/wics.101.
[25] C.A. Fukuchi, R.K. Fukuchi, M. Duarte, A public dataset of overground and treadmill walking kinematics and kinetics in healthy individuals, PeerJ 6 (2018) e4640.
[26] J.D. Rodríguez, G.J. Bermejo, A. Jayakumar, M.R. Lorente, O. R. Agujetas, S.F. Romero, Force and torque characterization in the actuation of a walking-assistance, cable-driven exosuit, Sensors 22 (11) (2022) 4309, https://doi.org/10.3390/s22114309.
[27] D.R. Jorge, J. Bermejo-Garcia, A. Jayakumar, F. Romero-Sánchez, F.J. Alonso, A synergy-based approach for the design of a lower-limb, cable-driven exosuit, ASME. J. Mech. Des. 144 (10) (2022), https://doi.org/10.1115/1.4054768 103302.
[28] V. Bartenbach, K. Schmidt, M. Naef, D. Wyss, R. Riener, Concept of a soft exosuit for the support of leg function in rehabilitation, in: IEEE International Conference on Rehabilitation Robotics (ICORR), 2015, pp. 125–130, https://doi.org/10.1109/ICORR.2015.7281187.
[29] J. Bermejo-García, D. Rodríguez Jorge, F. Romero-Sánchez, A. Jayakumar, F.J. Alonso-Sánchez, Actuation strategies for a wearable cable-driven exosuit based on synergies in younger and older adults, Sensors 23 (1) (2023) 261, https://doi.org/10.3390/s23010261.
[30] A. Rodríguez-Fernández, J. Lobo-Prat, J.M. Font-Llagunes, Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments, J. Neuroeng. Rehabil. 18 (1) (2021) 1–21, https://doi.org/10.1186/s12984-021-00815-5.