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Characterization of kinetic and kinematic parameters for wearable robotics

✉ Solis-Ortega Rodrigo D, Dehghani-Sanij Abbas A, Martinez-Hernandez Uriel

University of Leeds, Leeds, LS2 9JT, UK,
{el14rdso,a.a.dehghani-sanij,u.martinez}@leeds.ac.uk

Abstract. The design process of a wearable robotic device for human assistance requires the characterization of both kinetic and kinematic parameters (KKP) of the human joints. The first step in this process is to extract the KKP from different gait analyses studies. This work is based on the human lower limb considering the following activities of daily living (ADL): walking over ground, stairs ascending/descending, ramp ascending/descending and chair standing up. The usage of different gait analyses in the characterization process, causes the data to have great variations from one study to another. Therefore, the data is graphically represented using Matlab® and Excel® to facilitate its assessment. Finally, the characterization of the KKP performed was proved to be useful in assessing the data reliability by directly comparing all the studies between each other; providing guidelines for the selection of actuator capacities depending on the end application; and highlighting optimization opportunities such as the implementation of agonist-antagonist actuators for particular human joints.

Keywords: wearable robotics, gait analysis, lower limb, kinematics, kinetics.

1 Introduction

The characterization of kinetic and kinematic parameters (KKP), described as follows, is focused on wearable robotics applications for human assistance, such as exoskeletons, exosuits, soft orthoses, etc. The latter devices provide assistance by delivering rotational forces (torques) to the body joint of interest, using different types of actuators. The broad range of actuation technologies currently available has given birth to many functional prototypes capable of assisting human motions during several activities.

The design process of a wearable robotic device includes the characterization of both KKP for the human joints intended to be assisted which allows the device to be tailored to a particular application, whether assisting an elder adult or allowing a disable patient to walk. The effectiveness of each prototype is commonly assessed by measuring the metabolic cost reduction delivered to the user while performing an activity [1]. However, the latter requires specialized equipment. An alternative way is comparing the range of motion and torque delivered to the assisted joint with the values commonly found in humans during a certain activity. This type of data is available in gait analysis studies. In addition to the latter application, this data can be used as design guidelines when developing a wearable robotic device, e.g. the torque information can be used to choose the proper actuation technology. Therefore, the gait analysis data is commonly used in the development of wearable robotic devices since it can provide design guidelines specific to the activity of interest and can be used to assess the degree of assistance provided by a prototype.

Gait analysis studies usually provide KKP. The kinematic parameters describe the human body motion, e.g. the joint angle, velocity, and acceleration; whereas the kinetic parameters describe the forces causing this motion, e.g. joint torque and power. The most commonly implemented method to extract these parameters is motion capture. However, other technologies such as soft strain sensors [2], electrogoniometers [3], and inertial measurement units (IMU) have also been used. Lastly, it is important to mention that these studies differ between one another in many aspects, apart from the choice of technology, such as subjects' gender, age, weight, etc., as well as the setup of the experiments.

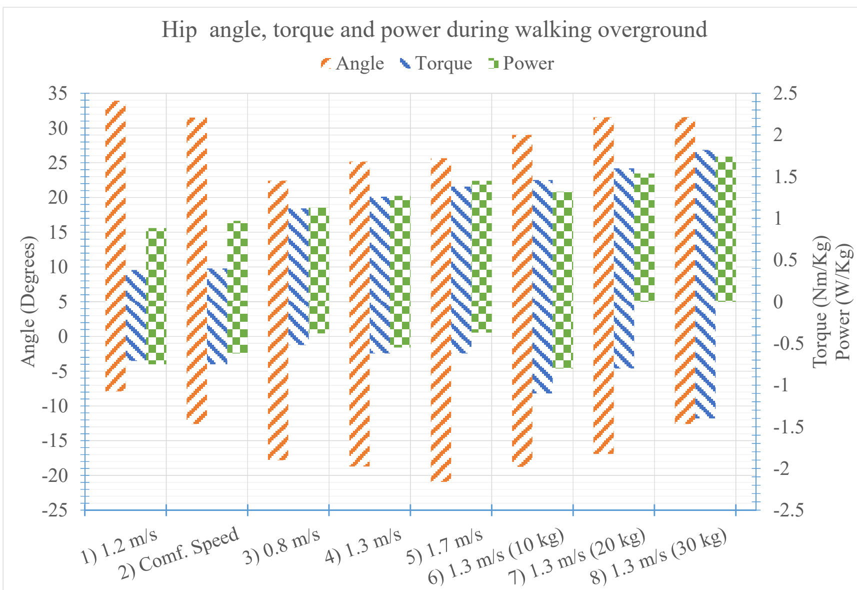

Fig. 1. Data compiled from several experiments for walking over ground activities. The weight next to the name of some activities dictates the load carried by the subjects during the experiment. The torque and power are presented in the same axis since their values share the same order of magnitude. The gait analysis studies are as follows: 1) [4], 2) [5], 3-8) [6].

This work is focused on describing the characterization process that, based on the extraction of the KKP from human lower limbs, can be used as guidelines in the design of wearable robotic devices. The gait analysis studies mentioned here were selected according to the activities of daily living (ADLs) of interest: walking, ascending/descending stairs, ascending/descending ramps and chair standing up. The data for the hip, knee and ankle joints is extracted and compiled. Furthermore, the data is visually represented in charts of clustered stacked bars in order to allow for quick comparisons to be made between different gait analysis studies. Finally, 12 charts were produced from the compiled data using Excel®, one of them is presented in Fig. 1 which concentrates the data for a single joint during different activities, in this case, variations of walking over ground. The parameters of the joint angle, torque and power are included. Activities are named to provide insight to the main features of the experiment, i.e. the walking speed and load carried by the subjects. Finally, the compiled data is presented in two more chart styles, in the following sections, to highlight the benefits of this graphic representation.

2 Gait Analysis Data

Gait Analysis studies provide the description of the performed experiment, including: the number of subjects in the group, subjects' characteristics such as age, weight, height, gender and health condition; experiment characteristics such as walking speed, ramp inclination, stairs geometry, initial sitting position and special conditions, such as, whether subjects are carrying a load or not. The subjects' characteristics are always presented in mean (average) values of the whole group. In a similar way, the derived data (torque and power) is presented in mean values and is normalized using the subjects' height, in the case of the gait cycle speed; and the subjects' weight, in the case of the torque of each joint. The normalization is appreciated in the units for torque and power in Fig. 1, being Nm/kg and W/kg respectively. The data used in the normalization process is usually provided as mean values of the subjects' group's height and weight. However, in some studies like the one in [5], the gait cycle speed is not explicitly provided nor it can be calculated because the normalization process is done considering each subject's characteristics and not the mean values of the subjects group. Again, this is reflected in Fig. 1, where the walking speed for activity 2) is not included in the name.

From one study to another, the subjects group is expected to be different and diverse in several characteristics. This diversity causes segmentation of the whole group, e.g. in the study performed in [4], there is a segmentation of the group in two different range of ages. One group included subjects from 22 to 72 years old, meanwhile, the subjects from the other group have ages ranged from 6 to 17 years old. The latter presented evidence of age-related differences which disproved the conclusions on previous works where these difference are non-existent. Nevertheless, when no significant difference is appreciated in the data despite the subjects' age diversity, the data is compiled into a single cluster and no segmentation is performed, such as the case in [5].

The usage of motion capture allows the extraction of the kinematic parameters, such as the joint angle. Similarly, the kinetics of the human body are obtained using force plates which measure the ground reaction forces, a required parameter to calculate the joint torque and power. Therefore, the set of parameters usually found in gait analysis studies contains the joint angle, joint torque, and joint power. The activity gait cycle is usually presented in a chart accompanied with tables highlighting the maximum, minimum and mean values of the gait cycle.

For the characterization of the human KKP, the values for the maximum and minimum of each parameter are of interest, more specifically, the differences between them. Most studies present these values in the form of tables and charts [6, 7], some of them even provide the whole experiment dataset [8]. When a data table is available, the extraction of the values is straight forward. Nevertheless, cases such as [9–13] do not provide any table and the data have to be extracted visually, decreasing the data accuracy, hence its reliability. Likewise, it can be the case for some studies to focus on specific features of the gait cycle, such as maximum and minimum values of each parameter; or even worse, not provide one or more of the parameters of interest (angle, torque or power).

3 Characterization of Lower Limb Parameters

The variations of the data from one experiment to another can be reduced by focusing on the range obtained from the difference between the maximum and minimum values of each parameter. As illustrated in Fig. 1, despite the variations between the maximum and minimum values from one experiment to another, the actual range of each parameter is similar among all the experiments. The mean range of motion for the hip joint angle throughout all the experiments showed in Fig. 1 (walking over-ground) was found to be 44.63 degrees. When comparing the latter mean range value with the range value of each experiment, the greatest variation between those is 18%. The previous calculation can be used to decide design parameters of the wearable robotic device to be developed, such as which range of motion should be covered by the device depending on which sector of the population is intended to be assisted; or if the mean range of motion value is used, the percentage of the focused population being covered. Nevertheless, the objective in representing the data visually, as in Fig. 1, is to allow quick comparisons with good accuracy, hence avoiding early calculations.

Table 1 contains the torque mean range of the hip joint during several ADLs. The data was extracted from a previously compiled table containing several clinical studies. The mentioned table is not presented in this work due to its large size. However, the obtained mean range values and the clinical studies used to extract the maximum and minimum values of the torque for each activity are provided in Table 1 which are sufficient enough to describe the benefits of visualizing the data graphically.

Table 1. Torque mean ranges for the hip joint during several ADLs. Each main activity is composed of several clinical studies with different parameters between one another.

Main Activity	Hip Torque Mean Range (Nm/kg)	Clinical Studies
Walking	-0.1875 – 1.5988	[4–6]
Stairs Ascending	0 – 1.27	[9, 10]
Stairs Descending	0 – 1.1275	
Ramp Ascending	-0.15 – 1.033	[11]
Ramp Descending	0 – 1.44	
Chair Stand Up	-0.4833 – 0.60	[12, 13]

The data presented in Table 1 is used to plot the chart illustrated in Fig. 2 using Matlab®, following a similar approach as the one presented in [14], where the range of motion of the knee joint is compiled into a chart for 11 different ADLs. The chart style used in Fig. 2 highlights two important design parameters: the actuators implemented in the wearable robotic device to be developed must be able to deliver torques in both clockwise and anti-clockwise directions, and the actual actuator torque capacity depending on the activities of interest.

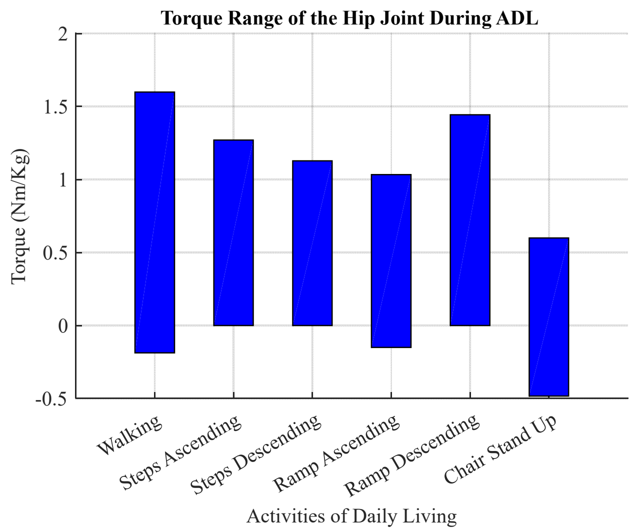

Fig. 2. Illustration of the range values of the torque during several activities. The values for the maximum and minimum torque are mean values obtained by averaging the data of all the different gait analysis experiments enclosed in one main activity. The data used to create this chart is presented in Table 1.

An alternative visual representation of the data available in gait analyses works to group the range of a specific parameter and comparing it with one of the subjects' physical characteristics, e.g. the age range. Fig. 3 illustrates the dependency of the subjects' age with the knee range of motion. The colour code used in Fig. 3, the age ranges and knee ranges of motion are presented in Table 2.

The chart shown in Fig. 3 concentrates the data from three different gait analyses, in which six age groups are contained. The approach used in Fig. 3 is to overlap areas of different colours, each area represents the range of motion of the knee for a specific age range. The area in which several areas intersect can be appreciated due to the enabled transparency property. Nevertheless, the areas where three and two areas are intersected are manually highlighted by a surrounding solid line and dotted line respectively, to improve their visualization. This simple intersection of areas can provide information regarding the required range of motion to be delivered by the wearable robotic device, depending the sector of the population focused on.

Table 2. Colour code used in Fig. 3 for each combination of age range and knee range of motion. The knee range of motion is provided in degrees. The clinical studies where the data was extracted from are also provided.

Colour Code	Knee Range of Motion (°)	Age Range (Years)	Clinical Study
Red	2.2 – 67.4	49 - 90	[14]
Green	5 – 66.5	6 - 17	[4]
Blue	4.5 – 63.5	22 - 72	
Yellow	0 - 69	18 - 30	[5]
Magenta	0 - 69	50 - 70	
Cyan	8 – 63.6	23 - 27	[6]

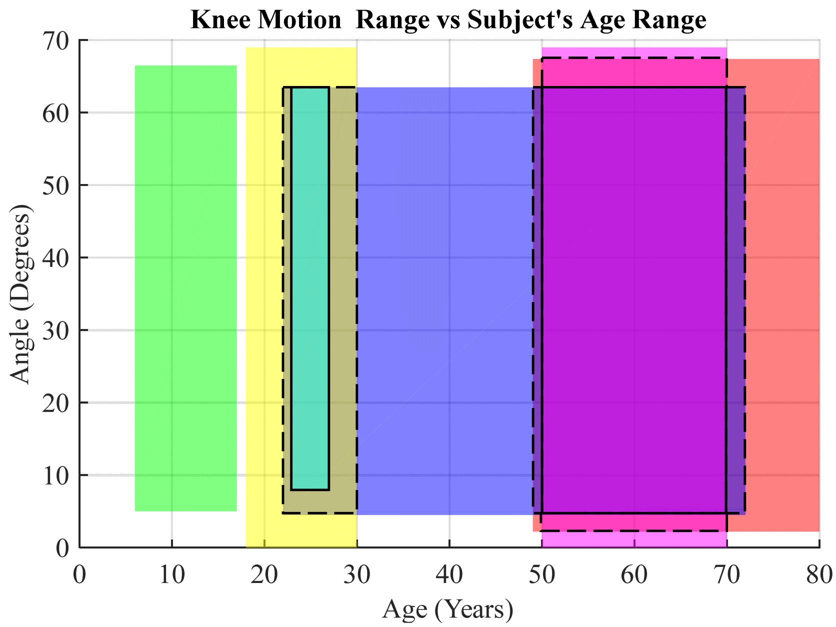

Fig. 3. Chart illustrating the comparison between subjects' age and the knee range of motion during walking over ground. The areas surrounded by solid lines and dotted lines represent the intersection between three and two areas, respectively. The overlapping squares highlight the great similarity among the range of motion despite subjects' age. The data used to create this chart is presented in Table 2.

For example, if a wearable robotic device was aiming to assist the population sector aged from 50 to 70 years old, then a range of motion of the knee joint from 5 to 63 would be enough to cover the mentioned population. The later range of motion is taken from the triple intersection of areas illustrated in Fig. 3, which can provide a certain degree of confidence since three different clinical studies were compared. This approach can be used to compare other characteristics, e.g. subject's weight against torque. Summarizing, the areas overlapping approach can provide guidelines to avoid oversizing of the wearable robotic device to be developed by analysing the intersection of different areas which ultimately provides a degree of confidence when deciding design parameters.

Lastly, the same visual presentation implemented in Fig. 1 is illustrated as follows in Fig. 4, in this case for the knee joint during several activities of stairs ascending/descending. The important detected feature is not the similarity among the range of motion, but the mirrored values shown for the torque parameter. In other words, the torque values required for descending stairs is completely opposite in direction and twice as big in magnitude as the one required for ascending stairs. The latter illustrates an optimization opportunity. When designing a wearable robotic device for human for human assistance, the actuator is chosen to satisfy a certain torque range of a particular activity. Without the characterization of the parameters performed, the actuator is most likely to be oversized to comply with the most demanding part of the activity. However, a different approach could be proposed: agonist-antagonist actuators; a technique implemented in several wearable robotic devices which at the same time complies with the actual functionality of the human musculoskeletal system.

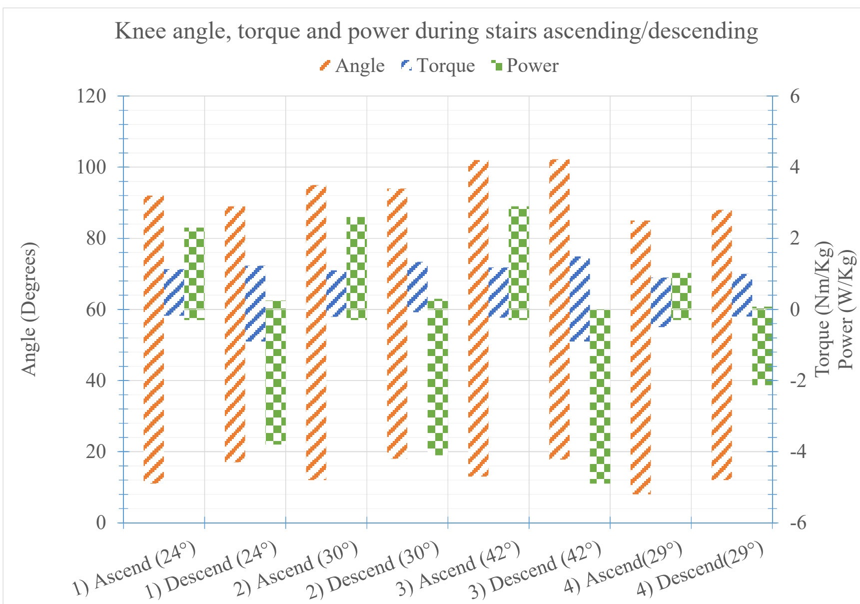

Fig. 4. Data compiled from several stairs ascending/descending experiments. The number enclosed in brackets represents the stairs slope. The parameters of torque and power are presented in the same axis since their values have the same order of magnitude. The gait analysis studies are as follows: 1)[10], 2- 4) [15].

4 Conclusion

The work presented here described the process of characterizing the human lower limb kinematics and kinetics parameters during some ADLs. The relevant information provided in gait analysis experiments was described, as well as possible challenges when extracting it. Data compiled for the activities of walking, ascending/descending stairs, ascending/descending ramps and chair standing up were presented in the form of clustered stacked bar charts.

The usefulness of compiling a data table and visually representing it was mentioned. The clustered stacked bar chart allowed quick and easy detection of similarities/differences between several clinical trials of the same activity. The similarity between the ranges of values of a specific parameter also dictates the reliability when implementing the data as design guidelines. The data feasibility can be corroborated by the chart style with subjects' age ranges against the knee ranges of motion by assessing the number of overlapping areas. In contrast, the spotted differences, as the ones for the knee torque values during ascending/descending stairs, are indicators for optimization opportunities where instead of using a single actuator to satisfy the torque range, an agonist-antagonist system could be more suitable. Moreover, the chart style with the ranges of motion versus activities facilitates the choice of the actuator type and dimension (depending on the activities of interest). Finally, the style used to represent the charts in this work was kept as simple as possible while providing useful information about the KKP. However, more complex plotting methods can be used, e.g. the patterned frames used in the chart of overlapping areas could be automatically created by the plotting software instead of being manually added, allowing a faster assessment of the feasibility of the data.

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