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Preliminary evaluation of an objective assessment approach from session data in exoskeleton-assisted gait rehabilitation after SCI

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Abstract— Exoskeleton-assisted gait rehabilitation is a promising complement to traditional motion rehabilitation programs for afflictions such as stroke or spinal cord injury. However, some challenges persist that hinder the translation of this approach to the clinical practice. One of these aspects is the objective assessment of patients' progress from information collected during exoskeleton-assisted therapy sessions with minimal hardware setup. In order to carry out an objective assessment with the data collected during the sessions, in this work: (1) we implement and compute a set of metrics (Harmonic Ratio, Joint Trajectory Correlation, and Intralimb Coordination) from data provided by the exoskeleton and two inertial motion units (IMUs) while subjects walked during their rehabilitation sessions, (2) we evaluate the capacity of the metrics to discriminate between the different patients' physical conditions, and (3) assess the correspondence of the patient evaluations using the mentioned metrics and traditional clinical scores. Our results show that Intralimb Coordination has the greatest capacity to discriminate between different physical states of the patients and presents the best correlation with their clinical assessment.

Clinical relevance— This work could guide clinicians and researchers to formulate a more objective assessment of progress of patients who have experienced a spinal cord injury using data collected during exoskeleton-assisted therapy sessions.

I. INTRODUCTION

The central nervous system (CNS) is the primary manager of the body's movements, senses, cognition and emotions ([1]). The injuries that typically compromise the CNS are neurodegenerative diseases and traumatic injuries ([1]), such as traumatic spinal cord injuries induced by external impacts. The consequences of this type of injury vary depending on the compression features (how, where, the intensity level, etc.) ([2]). The Spinal Cord Injury (SCI), is a temporal or permanent change in the spinal cord or nerve function, which has an overall incidence of 16 to 19.4 injuries per million inhabitants every year in Europe ([3]).

Patients that have suffered injuries to the CNS have distinct needs in their personalized rehabilitation process which is determined by the type of trauma that caused the injury and their individual patient characteristics (age, morbidity, neural capability, among others) ([4]). A large percentage of SCI patients suffer from lifelong mobility restrictions ([5]), and ultimately rely on rehabilitation sessions focused on gait recovery. In order to recover motor functions, such as gait, the repetition of intensive task-oriented exercises is key for neuroplasticity activation and neurological deficit reduction ([6]–[8]). One way to perform this type of therapy is to use exoskeletons, which is more commonly used in rehabilitation centers due to encouraging results or for economic reasons ([9]). Exoskeletons offer the possibility to reduce manual work performed by physical therapists, increase efficiency and potentially avoid a common problem at the clinic: the limited time of the therapists ([9]).
Nowadays, there are several exoskeletons for lower limb function recovery: Hank, ReWalk, ARTHuR, LOPES, XoR, Honda:SMA, HAL, among others ([10]). Evidence exists regarding the efficacy of exoskeleton-based therapy for gait recovery. Several studies have shown the positive impact of exoskeleton-based therapy on walking speed [11], [12], precise movement [13], [14], autonomous movement [15], [16] and the patient's quality of life [5], [12].

Some metrics that would aid in the therapeutic evaluation should be established such as comprehensively sampling the evolution of each subject and planning the optimal personalized rehabilitation strategy. ([18], [19]). Studies that explore this type of metrics in exoskeleton based training, have been found for the upper arm [17]. However, exoskeleton based gait training evaluation has not been deeply studied.

In previous studies regarding objective assessment in exoskeleton-based gait rehabilitation, alternative exoskeleton designs, control strategies, or rehabilitation paradigms have been evaluated [20]–[23]. However, few studies focus on the use of information recorded during sessions as a tool to evaluate the progress of the patient's condition.

In [24], a study has been carried out to evaluate gait metrics that observe circumduction, foot clearance and stride length based on information collected from exosuit-integrated IMUs. The researchers performed a single post-stroke participant case study based on

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step segmentation calculated with zero velocity updates (ZUPTs). In [25], a methodology has been found where the authors use encoders, gyroscopes, inclinometers and force sensors located in a 7-DOF passive exoskeleton in order to measure joint angles, angular velocity and acceleration of the hip, knee and ankle aiming to estimate torques at the given joints and detect the gait phases. In [26], to estimate the kinematics and the torques at lower limb joints, a dynamic model based on Lagrangian mechanics has been proposed. The gait information required is obtained from encoders, axis inclinometers and axis accelerometers. Moreover, a gait phase detection is used to restrict the model based on different gait phases. In [27], a walking assessment is proposed based on the changes in kinetics and kinematics of the gait when wearing a Gravity Balancing Exoskeleton (GBO). Data from three stroke patients and four healthy patients was collected from joint encoders and interface torque sensors to establish the hip and knee range of motion, the weight bearing on the limbs, and the walking speed. These parameters were evaluated in a chronic stroke patient that followed a 6-week training with the GBO.

Most of the quantitative measurements found in the described articles are not easy for the physical therapist to interpret. The mapping of these concepts into functional characteristics is not straightforward. The reason for this is that metric results do not indicate the degree of deviation from the reference values, which in most cases is another aspect/data point that is lacking. This work aims to implement objective metrics that are easier to interpret without complex additional equipment, test them under real-life conditions throughout a rehabilitation program with SCI patients with different conditions and limitations, and compare the results to traditional clinical scores.

II. MATERIALS AND METHODS

A. Studied subjects

Inclusion criteria for this work required the subjects to have: an age between 18 and 80 years, a weight of less than 100 kg, sufficient cognitive capacity to understand the study (MMSE>24), paraplegia due to an injury on the spinal cord and ability to stand with some external support. Due to the exclusion criteria, out of 13 volunteers, only four were selected (age 55.75 ± 10.71 years, and a partial lesion at the spinal cord 21.5 ± 14.1 years old). Non-chronic patients were excluded, in order to avoid the effects of spontaneous recovery during the first year after the injury ([28]). The patients' demographic and injury information is presented in Table I.

B. Instrumentation used

1) Hank exoskeleton: The exoskeleton used in this study is the Hank (Gogoa, Spain) [29]: a 6-active joint robotic rehabilitation system that allows physical and neuronal rehabilitation treatment that reinforces lower limb mobility. The exoskeleton provides two assistive modes: (a) ”Step mode”: the user takes one step at a time (b) ”Walking mode”: the user walks continuously.

Parameters	S1	S2	S3	S4
Age	55	44	70	54
Sex	female	male	male	male
Lesion	Tetraplegia	Paraplegia	Tetraplegia	Paraplegia
Injured zone	C7-D1	D12-L1	C5-C6	D7
Injury type	Incomplete	Incomplete	Incomplete	Incomplete
Injured year	1985	2000	2015	1986
External help	Crutches/Walker	Parallel bars	Walker	Crutches

TABLE I: Demographic and injury information of the subjects.

2) IMU: The subjects' movements were recorded with two STT-IWS, STT Systems [30], Inertial Measurement Units (IMU) that provide information about the position, orientation and acceleration of the limb where the sensors are attached.

C. Rehabilitation Protocol

16 rehabilitation sessions were performed, during eight consecutive weeks. A 40-minute rehabilitation session with the physical therapist was followed by a 40-minute exercise session wearing the Hank. The number of recordings at each session varied. Before each recording, the patients were allowed to practice with the exoskeleton briefly. The exoskeleton's assistive mode was selected in each session based on the subject's walking capabilities. Subjects with lower capabilities were rehabilitated in ”step mode”. Otherwise, the ”walking” mode was chosen. Patients were allowed to use additional support devices for the gait rehabilitation (see external help in Table I). Also, the therapist provided additional help to the patient (e.g., moving a leg to complete a step, support to keep balance, etc.), when required.

Three evaluation sessions of the Barthel ([31]) and Berg ([32]) scores were conducted by the therapist. The Barthel index (goes from 0 to 100, where 100 means total independence) assesses the ability of the subject to fulfill activities of daily living independently, including transfers (bed to chair and back), mobility on level surfaces and climbing stairs. The Berg balance scale (goes from 0 to 56, with a score greater than 40 indicating independence, a score greater than 20 and less than or equal to 40 indicating the need for assistance to walk, and a score less than or equal to 20 indicates the need to use a wheelchair) evaluates the subject's static and dynamic balance ability.

D. Recorded data

1) Angle and acceleration: One IMU was placed on the lower back to obtain the acceleration data (at 100Hz) of the pelvis in three directions: antero-posterior (AP), craneo-caudal (CC) and medium-lateral (ML). Due to the magnetic interference created between the HANK's power and control unit and the IMU, the angle and accelerations could not be recorded for long periods of time. Therefore, the recordings lasted four minutes maximum.

Another IMU was placed at the leg for synchronizing the information coming from the exoskeleton and the IMU system by aligning the curves for the left hip flexion on the time axis.

The information obtained from the exoskeleton (at 8Hz) contained the flexion angles of the right and left hips, knees and ankles.

2) Information recollection limitations: The number of rehabilitation sessions each subject attended was different due to personal reasons. Moreover, due to some hardware complications, the Hank could not be used for all sessions. The information about the recordings for each subject is specified in Table II.

Due to complications with the recording equipment or due to deviations from the established protocol, some recordings were found to be incomplete (without enough steps, without data from one or more joint angles), or with corrupted data (e.g. with unfeasible joint angle ranges). Therefore, not all recordings were usable for the analysis (the number of usable trials for each subject is specified in Table II). Furthermore, there were large differences in the amount of steps recorded for each subject. For example, some trials contain around 80 steps done continuously with the exoskeleton in the ”walking” mode, while others have only 12 steps in the ”step” mode.

Parameters	S1	S2	S3	S4
# of recordings	27	11	19	23
# of recordings with exoskeleton	21	9	14	20
# of usable exoskeleton recordings	9	6	11	10

TABLE II: Number of recordings performed by each subject

E. Computed metrics

Three metrics were computed based on the information captured in each session. The metrics were designed to express similarity (values from 0 to 100) between the patient and the healthy pattern in the assessed gait feature.

1) Intralimb coordination (IC): The Intralimb Coordination (IC) is a kinematic parameter that measures the coordination among different anatomical parts of each limb [33]. The studied elevation angles were the angles of the thigh, shank, and foot. Those angles were recorded by the exoskeleton sensors during sessions. Two IC values (one for each leg) were obtained in each session. The reference values for IC were obtained from a healthy gait pattern in [34], which were the baseline for comparisons. We computed the IC metric following the method in [35], adding a final step to obtain the similarity between the loadings obtained from a healthy pattern with those of the patient. First, we computed the principal component analysis (PCA) from the 3D curve formed by the elevation angles of the thigh, shank, and foot; using the Singular Value Decomposition method. Then, we obtained the factor loadings of each elevation angle on the first two principal components (loadings are the coefficients of the principal components). Then we computed the similarity (S_{ang}) of each angle loading ($\dot{L}_{ang}$) with respect to that of a healthy pattern (L_{ang}) as:

$$S_{angPC1} = (1 - |(|\dot{L}_{angPC1}| - |L_{angPC1}|)|) * 100 \quad (1)$$

$$S_{angPC2} = (1 - |(|\dot{L}_{angPC2}| - |L_{angPC2}|)|) * 100 \quad (2)$$

For each elevation angle, we selected the minimum similarity (M_{ang}) between (S_{angPC1} and S_{angPC2}) and computed the mean similarity of the three elevation angles (M_{thigh}, M_{shank}, M_{foot}).

$$M_{ang} = min(S_{angPC1}, S_{angPC2}) \quad (3)$$

$$IC = \frac{M_{thigh} + M_{shank} + M_{foot}}{3} \quad (4)$$

2) Harmonic ratio (HR): The HR measures gait symmetry ([36]). Data for the HR was obtained from the IMUs during sessions. Both even and odd harmonic components of the acceleration at the subject’s trunk were compared to those of an ideal gait pattern while walking, following the procedure specified in [36]. The acceleration was computed in three directions: CC, AP and ML. The ideal gait contains even harmonics both for AP and CC measurements in each stride (one step with each leg). However, as the ML is limb dependent, odd harmonics should be found ([37]). Stride by stride, the acceleration of the trunk was obtained. Based on the frequency spectrum of the signal and the Fourier coefficients, even and odd harmonics were calculated. The result of this metric is obtained with the ratio between the power of the considered k intrinsic harmonics over the total power of the signal (k intrinsic and extrinsic harmonics) multiplied by 100.

3) Join trajectory correlation (JTC): The JTC is a kinematic metric that measures the correlation between joint angle curves of the studied subject and those of a healthy pattern ([38]). A good correlation is obtained if curves have similar shapes and movement event lengths. The six studied joints are: both right and left ankles, hips and knees. Data was obtained from exoskeleton measurements done during sessions. The protocol followed to obtain the JTC extended the Linear Length Normalization defined in [38]. The reference values for the angle curves were obtained from [34]. Session and healthy angle values were normalized in length and regularized. A temporal shift was applied to maximize correlation. Negative values were set to 0 and positive values were multiplied by 100.

F. Data processing

Once all the data was collected and visualized, some trials were rejected. The acceptance criteria included: angle values within the physiological range of motion, more than 5 steps recorded, and no problems detected with the recording of an angle. Among the chosen ones, the time range of interest was selected and the synchronization between the exoskeleton and the IMU data was performed. Then each metric was computed automatically.

G. Statistical analysis

The mean value and the standard deviation of each metric were calculated for each trial. Two-sided Wilcoxon tests were performed in order to compare the results obtained among subjects. The p-value selected for establishing the statistical significance was 0.05.

III. RESULTS AND DISCUSSION

A. Results obtained by the physiotherapist

A physical therapist evaluated each subject's physical state before, during, and after the rehabilitation. The average scores of the Barthel and Berg balance indexes are presented in Table III. The patients present differences in their functional capacity. Two of the subjects, S1 and S4, can be considered independent. Subject S2 suffers from low dependencies. Subject S3 has low scores in the Barthel and Berg scales, indicating serious dependencies and a poor equilibrium. Three of the subjects (S1, S2 and S3) need a wheelchair for daily mobility. Subject S4 can walk independently with crutches.

B. Metric results for each subject

The average values for the respective subjects for each metric are represented in Figure 1 (a). The average value and standard deviation added and subtracted to the average value are represented for each of the subjects in one graph (b-S1, c-S2, d-S3, e-S4).

C. Results of the comparison between subjects

To evaluate the capacity of the metrics to distinguish between the level of impairment in the subjects' gait, two-sided Wilcoxon tests were performed to check for significant differences among the mean metric values obtained for each subject. The results are shown in Table IV, where blue-colored boxes indicate statistically significant differences.

D. Discussion

The aforementioned results suggest that the IC has the greatest differentiation capability in the level of impairment of the gait among all metrics. Statistically significant differences were found in 83.33% of comparisons among subjects. Moreover, the gait impairment ranking of the IC closely matches the evaluation performed using the clinical scales. There is a slight difference in the ranking of S1 and S2 compared to the clinical scales. However, it is important to consider that their score in the Berg scale differs only by 2.5 points (out of a scale of 56 points).

The JTC metric seems only able to differentiate large differences in the subjects' gait impairment, obtaining significant differences in 50% of the cases, which mostly correspond to comparisons between S4 and the rest of the subjects.

Small differentiation capability has been found for the HR, obtaining significant differences in 33.3% of the comparisons between subjects. Moreover, the ranking of the subjects carried out by the HR does not match the ranking provided by the clinical scales (S3 received better scores than S1 and S2 in all cases).

It is important keep in mind that the evaluation of the metrics has been performed in a highly uncontrolled scenario that is faithful to the conditions and workflow of real-life robotic-assisted therapy sessions. In such a scenario, the device used to provide additional support (i.e. parallel bars, walker, crutches) could have strongly influenced some gait parameters (e.g. stability, symmetry) making the differences between the subjects' gait smaller in those features. Moreover, we hypothesize that the variability of the results may have increased due to changes in the exoskeleton assistive mode, changes of the external support device throughout the rehabilitation program, and even the help provided by the physical therapist. Such factors make it difficult to obtain a ranking of the subjects' level of gait impairment that completely matches those of the clinical evaluations. Nevertheless, the IC metric seems promising, and the results suggest that it could be used to quantify the level of the subjects' impairment throughout the duration of exoskeleton-assisted therapies.

This work, however, involved a small number of patients with a specific injury and there were factors that prevented us from gathering more data from the rehabilitation sessions. Therefore, it remains to proven that these results can be generalized and applied to a larger population or other injuries.

IV. Conclusion

The main idea of this work was to seek out insights on the utility of a set of objective metrics to evaluate the gait of patients with different levels of impairment in a scenario with the following constraints:

- The data to compute the metrics should come from the exoskeleton or minimal additional equipment.
- The data to compute the metrics should be acquired during rehabilitation sessions.
- Patients received personalized therapy, so they could:
  - use the exoskeleton in any of its assistive modes
  - receive help from the therapist to complete the rehabilitation exercises
  - use any additional device (e.g., crutches) to complete the rehabilitation exercises

For such a purpose, rehabilitation sessions of 4 subjects that wore the Hank exoskeleton and two IMU sensors were recorded. Three gait evaluation metrics were tested: IC, JTC and HR. The results of these metrics were studied and a statistical analysis was performed to check

Parameters	S1	S2	S3	S4
Barthel	95	75	31	100
Berg	17.5	15	3	51
Physical evaluation	Instability Lack of equilibrium Knee recurvatum	Knee recurvatum	Lack of hip balance Left knee recurvatum Right leg spasticity	Lack of stability

TABLE III: Subject evaluation during rehabilitation (average of the three assessments).

Fig. 1: a) Average metrics' values for all subjects. b-e) Average metrics' values and deviation range (+-1 std. dev.) for each individual subject.

Subjects	IC		JTC						HR		
	Right	Left	Knee R	Knee L	Ankle R	Ankle L	Hip R	Hip L	CC	AP	ML
S1-S2	🟦										
S1-S3		🟦		🟦					🟦		
S1-S4	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
S2-S3	🟦	🟦		🟦					🟦		🟦
S2-S4	🟦	🟦	🟦	🟦	🟦		🟦	🟦	🟦	🟦	
S3-S4	🟦	🟦	🟦	🟦	🟦		🟦	🟦			

TABLE IV: Statistical differences in Wilcoxon tests between subjects. No statistical difference (white) statistical difference (blue)

if the metrics were able to differentiate between the patients' functional capabilities, and match the ranking of the patients provided by clinical scales. The results suggest that in spite of the highly uncontrolled scenario, the IC metric could differentiate between the subjects' gait quality, closely following the patients' ranking provided by the Berg balance index. This preliminary evaluation indicates that IC could be used in clinical settings for the objective follow-up of the patient along the rehabilitation program. However, further investigation is needed to study the generalization of these results with a larger cohort of patients with varying degrees of damage caused by SCIs.

References

[1] F. T. S. M. Tuladhar A, Mitrousis N, "Central nervous system," Elsevier Inc., no. 1, 2014.

[2] M. C. LaPlaca, C. Simon, G. R. Prado, and D. Cullen, "Cns injury biomechanics and experimental models," Progress in brain research, vol. 161, pp. 13–26, 2007.

[3] G. Scivoletto, M. Miscusi, S. Forcato, L. Ricciardi, M. Serrao, R. Bellitti, and A. Raco, "The rehabilitation of spinal cord injury patients in europe," in Trends in Reconstructive Neurosurgery. Springer, 2017, pp. 203– 210.

[4] R. O'Connor and P. Murray, "Review of spinal cord injuries in ireland," Spinal Cord, vol. 44, no. 7, p. 445, 2006.

[5] K. Raab, K. Krakow, F. Tripp, and M. Jung, "Effects of training with the rewalk exoskeleton on quality of life in incomplete spinal cord injury: a single case study," Spinal cord series and cases, vol. 2, p. 15025, 2016.

[6] E. Taub, G. Uswatte, and T. Elbert, "New treatments in neurorehabiliation founded on basic research," Nature Reviews Neuroscience, vol. 3, no. 3, p. 228, 2002.

[7] R. P. Van Peppen, G. Kwakkel, S. Wood-Dauphinee, H. J. Hendriks, P. J. Van der Wees, and J. Dekker, "The impact of physical therapy on functional outcomes after stroke: what's the evidence?" Clinical rehabilitation, vol. 18, no. 8, pp. 833–862, 2004.

[8] B. H. Dobkin, A. Firestine, M. West, K. Saremi, and R. Woods, "Ankle dorsiflexion as an fmri paradigm to assay motor control for walking during rehabilitation," Neuroimage, vol. 23, no. 1, pp. 370–381, 2004.

[9] G. Chen, C. K. Chan, Z. Guo, and H. Yu, "A review of lower extremity assistive robotic exoskeletons in rehabilitation therapy," Critical ReviewsTM in Biomedical Engineering, vol. 41, no. 4-5, 2013.

[10] H. Lee, P. W. Ferguson, and J. Rosen, "Lower limb exoskeleton systems—overview," in Wearable Robotics. Elsevier, 2020, pp. 207–229.

[11] C. Tefertiller, K. Hays, J. Jones, A. Jayaraman, C. Hartigan, T. Bushnik, and G. F. Forrest, "Initial outcomes from a multicenter study utilizing the indego powered exoskeleton in spinal cord injury," Topics in spinal cord injury rehabilitation, vol. 24, no. 1, pp. 78–85, 2017.

[12] T. Afzal, S.-C. Tseng, J. A. Lincoln, M. Kern, G. E. Francisco, and S.-H. Chang, "Exoskeleton-assisted gait training in persons with multiple sclerosis: a singlegroup pilot study," Archives of physical medicine and rehabilitation, vol. 101, no. 4, pp. 599–606, 2020.

[13] M. Dru˙zbicki, A. Guzik, G. Przysada, A. Brzozowska-Mago´n, K. Cygo´n, G. Boczula, and H. Bartosik-Psujek, "Effects of robotic exoskeleton-aided gait training in the strength, body balance, and walking speed in individuals with multiple sclerosis: A single-group preliminary study," Archives of Physical Medicine and Rehabilitation, 2020.

[14] S. K. Agrawal, S. K. Banala, A. Fattah, V. Sangwan, V. Krishnamoorthy, J. P. Scholz, and W.-L. Hsu, "Assessment of motion of a swing leg and gait rehabilitation with a gravity balancing exoskeleton," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 15, no. 3, pp. 410–420, 2007.

[15] J. Mehrholz, S. Thomas, C. Werner, J. Kugler, M. Pohl, and B. Elsner, "Electromechanical-assisted training for walking after stroke," Cochrane Database of Systematic Reviews, no. 5, 2017.

[16] G. Carpino, A. Pezzola, M. Urbano, and E. Guglielmelli, "Assessing effectiveness and costs in robot-mediated lower limbs rehabilitation: a meta-analysis and state of the art," Journal of healthcare engineering, vol. 2018, 2018.

[17] de Los Reyes-Guzmán, A., Dimbwadyo-Terrer, I., Pérez-Nombela, S., Monasterio-Huelin, F., Torricelli, D., Pons, J. L., Gil-Agudo, A. (2017). "Novel kinematic indices for quantifying

upper limb ability and dexterity after cervical spinal cord injury." Medical biological engineering computing, 55(5), 833-844.

[18] J. F. Veneman, "Some considerations on benchmarking of wearable robots for mobility," in Wearable Robotics: Challenges and Trends. Springer, 2017, pp. 225–229.

[19] M. Gittler and A. M. Davis, "Guidelines for adult stroke rehabilitation and recovery," Jama, vol. 319, no. 8, pp. 820–821, 2018.

[20] C. Di Natali, T. Poliero, M. Sposito, E. Graf, C. Bauer, C. Pauli, E. Bottenberg, A. De Eyto, L. O'Sullivan, A. F. Hidalgo et al., "Design and evaluation of a soft assistive lower limb exoskeleton," Robotica, vol. 37, no. 12, pp. 2014–2034, 2019.

[21] S. Das, D. N. Das, and B. Neogi, "Lower limb movement analysis for exoskeleton design," in 2019 IEEE Region 10 Symposium (TENSYMP). IEEE, 2019, pp. 759–764.

[22] J. Wang, Y. Pang, X. Chang, W. Chen, and J. Zhang, "Mechanical design and optimization on lower limb exoskeleton for rehabilitation," in 2019 14th IEEE Conference on Industrial Electronics and Applications (ICIEA). IEEE, 2019, pp. 137–142.

[23] R. Lu, Z. Li, C.-Y. Su, and A. Xue, "Development and learning control of a human limb with a rehabilitation exoskeleton," IEEE Transactions on Industrial Electronics, vol. 61, no. 7, pp. 3776–3785, 2013.

[24] Arens, Philipp, et al. "Real-time gait metric estimation for everyday gait training with wearable devices in people post-stroke." Wearable Technologies 2, 2021.

[25] K. Kanjanapas and M. Tomizuka, "7 degrees of freedom passive exoskeleton for human gait analysis: Human joint motion sensing and torque estimation during walking," IFAC Proceedings Volumes, vol. 46, no. 5, pp. 285–292, 2013.

[26] J. Bae, K. Kong, and M. Tomizuka, "Real-time estimation of lower extremity joint torques in normal gait," IFAC Proceedings Volumes, vol. 42, no. 16, pp. 443–448, 2009.

[27] S. K. Agrawal, S. K. Banala, A. Fattah, V. Sangwan, V. Krishnamoorthy, J. P. Scholz, and W.-L. Hsu, "Assessment of motion of a swing leg and gait rehabilitation with a gravity balancing exoskeleton," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 15, no. 3, pp. 410–420, 2007.

[28] J. Hou, Z. Xiang, R. Yan, M. Zhao, Y. Wu, J. Zhong, L. Guo, H. Li, J. Wang, J. Wu et al., "Motor recovery at 6 months after admission is related to structural and functional reorganization of the spine and brain in patients with spinal cord injury," Human brain mapping, vol. 37, no. 6, pp. 2195–2209, 2016.

[29] Gogoa. (2021) Why use an exoskeleton to rehabilitate? [Online]. Available: https://en.gogoa.eu/hank

[30] S. STT INGENIER´IA Y SISTEMAS. (2021) Stt-iws imu. STT INGENIER´IA Y SISTEMAS, S.L. [Online]. Available: https://www.stt-systems. com/motion-analysis/inertial-motion-capture/ stt-iws/?gclid=EAIaIQobChMIsp-BuV5AIVBVXTCh1WrwwyEAAYBCAAEgJ-8 D BwE

[31] C. Collin, D.Wade, S. Davies, and V. Horne, "The barthel adl index: a reliability study," International disability studies, vol. 10, no. 2, pp. 61–63, 1988.

[32] S. W. Muir, K. Berg, B. Chesworth, and M. Speechley, "Use of the berg balance scale for predicting multiple falls in community-dwelling elderly people: a prospective study," Physical therapy, vol. 88, no. 4, pp. 449–459, 2008.

[33] J. A. Barela, J. Whitall, P. Black, and J. E. Clark, "An examination of constraints affecting the intralimb coordination of hemiparetic gait," Human Movement Science, vol. 19, no. 2, pp. 251–273, 2000.

[34] D. J. Au C. (2021) Gait 2392 and 2354 models. [Online]. Available: https://simtk-confluence.stanford.edu: 8443/display/OpenSim/Gait+2392+and+2354+Models

[35] J. W. Chow and D. S. Stokic, "Intersegmental coordination of gait after hemorrhagic stroke," Experimental brain research, vol. 233, no. 1, pp. 125–135, 2015.

[36] I. Pasciuto, E. Bergamini, M. Iosa, G. Vannozzi, and A. Cappozzo, "Overcoming the limitations of the harmonic ratio for the reliable assessment of gait symmetry," Journal of biomechanics, vol. 53, pp. 84–89, 2017.

[37] H. B. Menz, S. R. Lord, and R. C. Fitzpatrick, "Acceleration patterns of the head and pelvis when walking on level and irregular surfaces," Gait posture, vol. 18, no. 1, pp. 35–46, 2003.

[38] N. E. Helwig, S. Hong, E. T. Hsiao-Wecksler, and J. D. Polk, "Methods to temporally align gait cycle data," Journal of biomechanics, vol. 44, no. 3, pp. 561–566, 2011.