Human Movement Science 66 (2019) 521–528

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

# Pendular energy transduction in the different phases of gait cycle in post-stroke subjects

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ARTICLE INFO

*Keywords:*
Stroke
Gait analysis
Energy expenditure
Locomotion

ABSTRACT

*Main:* To analyze spatiotemporal gait parameters and the body center of mass (CoM) energy transduction at self-selected speed walking in a group of older patients with stroke.
*Methods:* A cross-sectional study, fifteen subjects with 4.06 years post-stroke hemiparesis (eleven men and four women) and fifteen healthy subjects (four men and eleven women) participate in this study. Pendulum-like determining variables; Recovery (R) and Congruity percentage (%Cong) were analyzed in addition to immediate pendular re-conversion (Rint) during the phases in which the gait cycle is usually divided in clinical evaluations.
*Results:* Healthy subjects walked faster that stroke group ($p = 0.001$). %Cong was significantly higher in post-stroke respect to healthy subjects ($p = 0.05$). Rint showed significant differences between the groups for all phases ($p = 0.05$). The relation between speed and R was confirmed, for healthy ($r = 0.67$, $p = 0.006$) and post-stroke subjects ($r = 0.851$, $p = 0.001$), %Cong y Rint ($r = -0.79$, $p = 0.001$), ($r = -0.93$, $p = 0.001$) and periods of double support ($r = -0.76$, $p = 0.001$), ($r = 0.69$, $p = 0.004$) respectively.
*Conclusion:* Alteration of pendular mechanism in subjects post-stroke is associated mainly with energy transduction; mechanical energy recovered during double support phases in healthy and post-stroke subjects follows a different trend, in post-stroke subjects, a longer duration of the double support is associated with less energy loss.

## 1. Introduction

The body center of mass (CoM) is a key factor in the analysis of normal and pathological human gait, as it reflects the motion of the whole body (Iida & Yamamuro, 1987). Considering kinetic ($Ek$ = ½ $mv^2$) and gravitational potential energy (**$Ep$** = m g h), where $m$ is body mass, $v$ speed of CoM, $h$ the height of CoM and $g$ gravitational acceleration. During healthy level walking, the exchange between $Eh$ (kinetic energy in the forward direction) and $Ev$ (gravitational potential energy more kinetic in the vertical) results in a total mechanical energy ($Et = Eh + Ev$) of CoM, with a smaller change over the stride compared to the two components when taken separately (Cavagna, Heglund, & Taylor, 1977; Cavagna, Thys, & Zamboni, 1976). The storage and use of $Eh$ and $Ev$ in each step depends on three factors: the phase relation between the two types of energy within a step; the relative magnitude of both energies; and the degree of symmetry between them. This mechanical energy transduction is associated with the inverted pendulum/rolling egg paradigm (Margaria, 1976). The pendulum-like mechanism is classically evaluated over an entire step by measuring the energy

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https://doi.org/10.1016/j.humov.2019.06.006
Received 24 December 2018; Received in revised form 16 May 2019; Accepted 8 June 2019
Available online 17 June 2019

recovery (R) and Congruity percentage (%Cong). R is a parameter to quantify the ability to save mechanical energy by using a pendulum-like paradigm (Cavagna et al., 1976) and %Cong corresponds to the temporal proportion of the cycle during which the *Eh* and *Ev* fluctuate in the same direction. When walking on level ground, R varies with changes in stride length (Saibene & Minetti, 2003) and walking speed (Cavagna et al., 1976), For R to achieve high values (60–65%), %Cong should be as low as possible (Cavagna, Willems, Legramandi, & Heglund, 2002; Saibene & Minetti, 2003). The amount of muscular work required to walk depends on the degree of deviation from an optimal situation of mechanical energy variations (Cavagna et al., 1977).

Any factor that alters the displacement of CoM affects both R and %Cong (Willems, Schepens, & Detrembleur, 2012) and therefore walking efficiency (Saibene & Minetti, 2003; Willems et al., 2012); this happens, for example, when walking on ground of varying softness (Lejeune, Willems, & Heglund, 1998) or with a sloping terrain (Dewolf, Ivanenko, Lacquaniti, & Willems, 2017; Gomenuka, Bona, da Rosa, & Peyre-Tartaruga, 2016). However, R and %Cong are computed over the whole stride and so do not allow us to understand how energy transduction changes throughout the different phases of the gait cycle (Dewolf et al., 2017). For this reason, it is not possible through these values to establish an association between the actions that occur in the different phases of the gait cycle examined in clinical analysis (Baker, 2006) and the energy saves via pendulum mechanisms. Instantaneous recovery of mechanical energy ($R_{inst}$), calculated from the absolute value of the changes in *Eh*, *Ev* and *Et* into equal time intervals during step period (Cavagna et al., 2002), allows the evaluation of the transduction of mechanical energy during the different phases of a gait cycle. To the best of our knowledge, few studies have measured changes in this transduction within the cycle in pathological gait, as has been performed in normal level gait (Cavagna et al., 2002) and with different slopes (Dewolf et al., 2017; Gomenuka et al., 2016). Besides, in the studies that have used $R_{int}$, the temporal division of the cycle is not based on the phases of the gait cycle considered in clinical studies (initial double support, single support, final double support and swing) (Lakany, 2008). This approach could be useful for clinical gait analysis in patients with an asymmetrical gait, such as post-stroke subjects, since it would facilitate the joint analysis of the tasks and objectives of each phase with pendular energy transduction, which is associated with efficiency; a clear explanation of this relationship can be found in (Saibene & Minetti, 2003).

Stroke is a leading cause of severe long-term disability (Benjamin et al., 2017) that impacts nearly 15 million people worldwide each year (Mackay and Mensah, 2018). Walking dysfunction occurs in more than 80% of stroke survivors (Duncan et al., 2005). Stroke survivors typically walk asymmetrically at a lower speed (Chen, Patten, Kothari, & Zajac, 2005; Patterson et al., 2008); temporal measures are often used to describe stroke patients' asymmetry (Patterson et al., 2008). In these patients, the support phase of both lower limbs occupies a large part of the walking cycle. The simple support of the unaffected limb is proportionally greater than that of the affected limb. A greater percentage of the cycle corresponds to the phase of double support, and the double support in which the affected limb is preparing for takeoff (backwards with respect to the unaffected limb) is longer than the contralateral one (Goldie, Matyas, & Evans, 2001). The spatial measures are less consistent given the high degree of variability. The stride length is shorter and typically has a decreased stance phase and prolonged swing phase of the paretic side (Perry & Burnfield, 2010). The difference in the length of the step is noteworthy when the lower paretic limb is compared to the non-paretic limb. In the first case, the step is usually longer than in the second.

Regarding the behavior of the CoM of these patients, it has been observed that changes in the kinematics of gait (Farris, Hampton, Lewek, & Sawicki, 2015; Ramos Arim, Fábrica Barrios, Silva Pereyra, & Camarot González, 2017) alter pendular behavior (Detrembleur, van den Hecke, & Dierick, 2000; Ramos Arim et al., 2017). The CoM of these patients can present vertical oscillations of up to 7 cm (Detrembleur et al., 2000). Although previous studies have noted a relationship between R approximately 20% below average (Detrembleur et al., 2000; Farris et al., 2015) and gait asymmetry post-stroke using spatiotemporal measures (Balasubramanian, Bowden, Neptune, & Kautz, 2007; Mahon, Farris, Sawicki, & Lewek, 2015; Patterson et al., 2008), the energetic analysis of each phase of the cycle has not yet been carried out.

The current study aimed to analyze spatiotemporal gait parameters and the CoM energy transduction at self-selected speed walking in a group of older post-stroke patients. The pendulum-like determining variables R and %Cong were analyzed, and we defined $R_{int}$ during initial double support, single support, final double support and swing. We used these four phases instead of the division proposed by Cavagna et al. (2002) to perform an analysis similar to the effects of being able to establish a correspondence with the angular actions; this is compatible with the descriptive or clinical analysis of gait. We hypothesized that the $R_{int}$ values of each phase are likely to deteriorate in stroke subjects in correspondence with spatiotemporal changes and consider that such an approach can lay the basis for a complete functional evaluation of the locomotion of stroke patients.

## 2. Methods

### 2.1. Design

An observational, analytical and transversal study based on a 3D reconstruction of the walk will be carried out, where the sample was obtained by convenience. All the procedures of this investigation were carried out in accordance with the ethical norms concordant with the Declaration of Helsinki. The ethics committee of Hospital de Clínicas approved studies conducted by Dr. Manuel Quintela (reference number: 90/16). Informed written consent was obtained from all participants before the study.

### 2.2. Subjects

Fifteen subjects with 4.06 years post-stroke hemiparesis (eleven men and four women) and fifteen healthy subjects (four men and eleven women) participated in this study. They were recruited from the Department of Rehabilitation and Physical Medicine of the

**Table 1**
Physical characteristics (mean and standard deviation) of participants in the study groups.

| Variable | HG Mean (SD) (n = 15) | SG Mean (SD) (n = 15) | p Value |
|---|---|---|---|
| Age (years) | 64.0 (3.3) | 64.9 (4.0) | 0.491 |
| Body mass (kg) | 63.9 (9.1) | 78.5 (10.9) | $< 0.001^{***}$ |
| Height (m) | 1.61 (0.06) | 1.69 (0.04) | $< 0.001^{***}$ |
| hCoM (m) | 0.76 (0.07) | 0.85 (0.04) | $< 0.001^{***}$ |

SD: Standard deviation, GH: Healthy Group, SG: Stroke Group. The hCoM corresponds to the height of CoM from the floor when the subject is standing in an anatomical position this value was used to make a precise determination of the relative speed by means of the Froude number. $^{*}$ $p < 0.05$. $^{**}$ $p < 0.01$. $^{***}$ $p < 0.001$.

Hospital de Clínicas. The main characteristics of both groups are presented in Table 1. The inclusion and exclusion criteria were defined according to the works of previous studies (Caty, Detrembleur, Bleyenheuft, & Lejeune, 2009; Mahon et al., 2015). We selected subjects between 50 and 75 years old in the chronic stage of stroke with more than six months of evolution. All the subjects of this group presented hemiparesis secondary to stroke and the ability to walk independently without an assistive device for 5 min. The exclusion criteria for this group included: 1) Botox injection to the lower limbs in the three months preceding testing; 2) a musculoskeletal, cardiorespiratory, metabolic or additional neurological disorder that could affect gait or compromise the participant's understanding of the proposal. The healthy subjects selected were between 50 and 75 years old at the time of the study. They were independent in their daily living activities and could walk without assistance or pain. Neither group had cognitive disorders or mild cognitive impairments. Furthermore, there the Montreal Cognitive Assessment test (MoCA) scores were greater than or equal to 19 points (Muñoz & Medina Sánchez, 2000).

### *2.3. Measurements*

The data records were made in the Research Unit in Biomechanics of Human Locomotion, Hospital of Clinics of the University of the Republic, Uruguay. The environment was at a temperature of 21 °C to avoid increased spasticity (Montes, Pérez, Ortega, & Zufia, 2009). Individuals were prepared with appropriate clothing, and reflective markers were placed on 45 anatomical references to make a 3D reconstruction of the whole body. Four markers were placed on participants' heads: left front head, right front head, left back head and right back head. Five markers were placed on the trunk: 7th Cervical Vertebrae, 10th Thoracic vertebrae, clavicle, xiphoid process of the sternum, half of the right scapula. Eight markers were placed on each upper limb: acromioclavicular joint, shoulder rotation center, arm between the markers of the shoulder and the elbow, lateral epicondyle, forearm between the elbow and wrist markers, lateral wrist marker, medial wrist marker and under the head of the second metacarpal. Four markers were placed on the pelvis: left anterior superior iliac spine, right anterosuperior iliac spine, left posterosuperior iliac spine and right posterosuperior spine iliac. Finally, eight markers were placed on each lower limb: greater trochanter of the femur, lateral distal third of the thigh, surface lateral epicondyle of the knee, over the distal third of the calf, lateral malleolus on an imaginary line passing through the transmaleolar axis, calcaneus, head of the second metatarsal and head of the fifth metatarsal.

Eight cameras (Bonita B10) operating at 100 Hz and connected to the Vicon Motion System (Oxford Metrics Ltd., Oxford, UK) allowed us to register the kinematic position data for each marker using Vicon's Nexus 2.4 software. Participants walked on a flat surface 10 m in length and 4 m in width at a self-selected speed. Between five and 10 records were made for each participant. Two strides of the central section were considered for the analysis in order to avoid inertial or braking effects, obtaining six to 10 data of each variable per participant.

### *2.4. Data management and processing*

Each stride data was processed using algorithm routines written in Matlab R2018a® (Mathworks, Inc.). The kinematic data were first low-pass filtered with a fourth-order zero-lag Butterworth filter with a cut-off frequency of 6 Hz. Subsequently, moments of foot contact and take-off were determined from the vertical velocity curves of the markers of the heel and toe. These moments were considered to define the stride phases: initial double support, single support, final double support and swing. Two types of variables were determined, spatiotemporal and associated with energy transduction in the CoM. The spatiotemporal variables considered were: Stride length (LC), Froude number ($Fr^{1/2} = v/\sqrt{gl}$) where v is the speed of progression (metres per second), g is acceleration due to gravity (9.81 $m.s^{-2}$) and l is leg length, in metres), mean speed (VM), step length for each limb, reference (LPr) and not reference (LPnr), cadence (steps/minute) and relative duration of each phase of stride, initial double support (DSi), single support (SS), final double support (DSf) and swing (S). For the Stroke group, the strides and phases were defined considering as reference the unaffected limb. In this way, during DSi the affected limb is behind the healthy limb; SS corresponds to the unaffected side. In DSf, the affected member is in front, and during the S the subject is supported on the affected limb. To determine the different contacts and take-offs, we used the vertical and antero-posterior velocity records of the markers of the feet. This method has been tested in our laboratory in conjunction with force platform records (unpublished data) and allows us to accurately identify events without conditioning the locomotion of the subject.

To determine the variables associated with CoM energy reconversion, segmental mass, a segmental CoM position and segmental radius of gyration were estimated from anthropometric tables proposed by Winter (2009). Owing to the importance of accurately

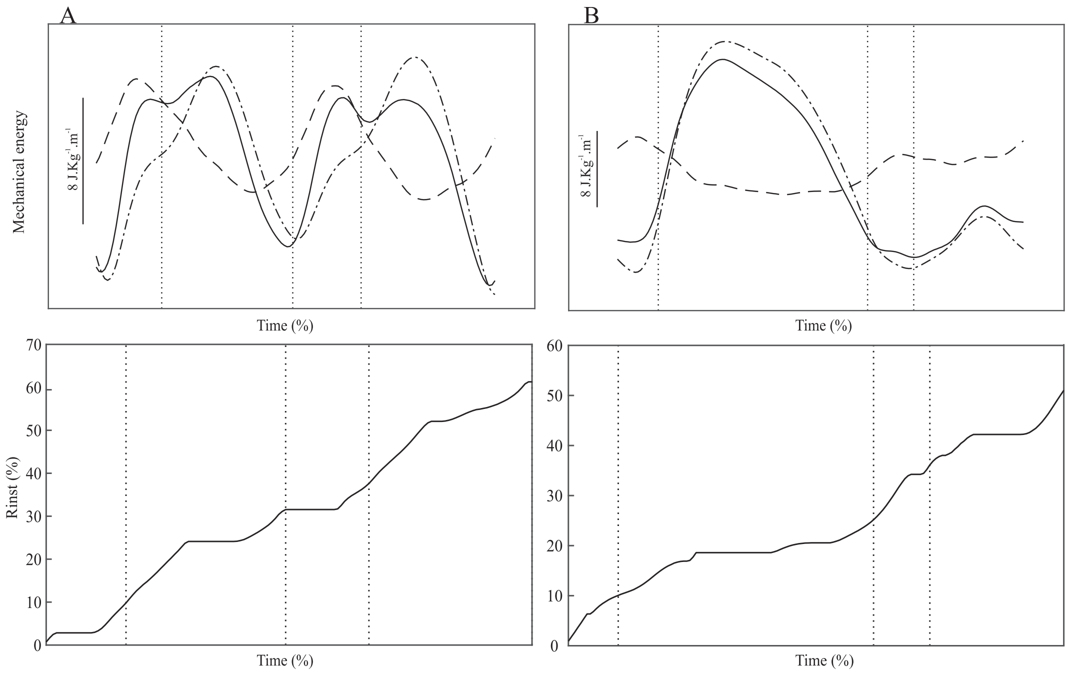


**Fig. 1.** The two graphs above show the variations of Eh (dashed line), Ev (dashed point line) and Et (solid line) during the percentage of the cycle for both a control subject (A) and a stroke patient (B). The energy values appear normalized in order to better visualize their exchanges during cycle, based on these variations were determined Wh, Wv and Wext. In the lower panel are presented the corresponding Rinst variations to each case. The dashed vertical lines indicate the limits of the different periods in the cycle.

locating the CoM from the kinematic data, we developed a spatial model considering the criteria of previous work (Nardello, Ardigo, & Minetti, 2011).

R was quantified using the method proposed by Cavagna et al. (1976), as described by Eq. (1):

$$R= ((Wv+Wh-Wext)/(Wv + Wh)) \times 100 \tag{1}$$

Were Wh is the horizontal external mechanical work, Wv is the vertical work and Wext is the external mechanical work. Wh plus Wv is the summation, over a stride, of all the increases in horizontal and vertical energies respectively (Saibene & Minetti, 2003), the explanation of how the calculations of Wh and Wv were addressed are presented in (Willems, Cavagna, & Heglund, 1995)

The %Cong was determined as the number of frames in which d(Eh)/dt and d(Ev)/dt have opposite sign divided by the total number of frames in a gait cycle × 100% (Cavagna & Kaneko, 1977).

The recovery of mechanical energy at each instant of the stride was calculated from the absolute value of the changes, both positive and negative increments, in Ev, Eh and Et during each time interval. To compare the energy transduction within the step in different subjects, the step cycle was divided into four periods (Vancampfort et al., 2018), and values of cumulative recovery were calculated for the experimental tracings for each period of time. All the details of the calculations performed are described in (Cavagna et al., 2002). So they were obtained, for DSi; recovery initial double support (RiDSi), for SS; recovery single support (RiSS), for DSf; recovery final double support (RiDSf) and for recovery swing (RiS) (Farris et al., 2015). Fig. 1 presents the result of partial processing for a control subject and a patient, there can see energy variations considered for the calculations in this work together with the corresponding changes in Rinst.

### *2.5. Data analysis and estimated sample size*

Based on previous studies that present variables similar to those determined in this proposal, we estimated the effect size to be 0.40 (Donelan, Shipman, Kram, & Kuo, 2004). With this effect size an alpha of 0.05, beta power of 0.80 and a minimum of 12 subjects per group were deemed appropriate to detect statistically significant differences in spatiotemporal and CoM energy transduction measures selected between groups. Descriptive data are presented as mean and standard deviation (SD) values. Normality assumptions were tested using the Shapiro-Wilk test and also the Levene test to check the equality of variances. Independent sample t-tests were used to compare differences between the groups. Pearson correlation coefficients were calculated to examine the relationships between the variables. Statistical significance was set at $P \leq 0.05$. All statistical analyses were performed using JASP version 0.9.0.1

**Table 2**
Spatiotemporal gait measurements of participants in the study groups.

| Variable | HG Mean (SD) (n = 15) | SG Mean (SD) (n = 15) | p Value |
|---|---|---|---|
| Froude number | 0.42 (0.04) | 0.21 (0.06) | < 0.001*** |
| VM (m/s) | 1.15 (0.11) | 0.59 (0.15) | < 0.001*** |
| LC (m) | 1.12 (0.07) | 0.82 (0.13) | < 0.001*** |
| Cadence (steps/min) | 110.8 (5.8) | 68.8 (24.9) | < 0.001*** |
| Lpr (m) | 0.62 (0.03) | 0.45 (0.05) | < 0.001*** |
| LPnr (m) | 0.6 (0.03) | 0.37 (0.09) | < 0.001*** |
| DSi (%) | 7.99 (2.65) | 11.41 (2.87) | 0.002** |
| SS (%) | 41.71 (3.16) | 50.6 (3.9) | < 0.001*** |
| DSf (%) | 8.21 (3.32) | 8.3 (2.03) | 0.803 |
| S (%) | 4.21 (2.9) | 29.7 (3.3) | < 0.001*** |

SD: Standard deviation, GH: Healthy Group, SG: Stroke Group, VM: Mean Speed, LC: Stride length, LPr: step length for each limb, reference, LPnr: step length for each limb, not reference, Dsi: initial double support, SS: single support, DSf: final double support, S: swing. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

## 3. Results

The spatiotemporal variables considered in this work together with the results of the comparisons between both groups (Table 2). The walking speed spontaneously adopted by Stroke subjects was significantly slower in both absolute and relative terms than those of the healthy group. All the spatiotemporal variables considered were significantly altered in the subjects with Stroke (p = 0.001), with the exception of the period of double support during which the lower limb of the affected side is located in front of the healthy limb.

The results and comparisons of the pendulum-like determining variables, R, %Cong and $R_{int}$, accumulated during the entire cycle and the phases in which the cycle is usually divided into clinical evaluations is illustrated in Table 3. Additionally, to facilitate discussion we included in this table the values of mechanical work on which the calculations are based.Table 4.

The existence of significant correlations between the speed (Froude number) and the standard pendulum recovery measure (R) was confirmed, (r = 0,67, p = 0.006) for healthy subjects (r = 0,851, p = 0.001) and for post-stroke subjects. A high and significant correlation was found between %Cong and $R_{int}$ for both groups, healthy (r = −0.79, p = 0.001) and post-stroke (r = −0.93, p = 0.001). On the other hand, the values of Wext, Wv and Wh were not correlated with $R_{int}$ in the post-stroke subjects, and only Wext presented a high and significant correlation for healthy subjects (r = −0.69, p = 0.004).

The correlation between the duration and the energy recovered for each phase was evaluated to establish the first level of discussion of the spatiotemporal gait parameters and the CoM energy transduction. We did not find a correlation between the duration of the simple support phases (SS and S) and the energy recovered there (RiSS and RiS). However, significant correlations were established in the periods of double support. DSi - RiDSi (r = −0.76, p = 0.001) and (r = 0.69, p = 0.004) for healthy subjects and post-stroke, respectively. Additionally, DSf - RiDSf values were r = −0.69, p = 0.004 and r = 0.60, p = 0.017 for healthy subjects and post-stroke, respectively.

**Table 3**
Measures associated with the CoM energy transduction of participants in the study groups.

| Variable | HG Mean (SD) (n = 15) | SG Mean (SD) (n = 15) | p Value |
|---|---|---|---|
| Wext | 0.36 (0.05) | 0.55 (0.13) | < 0.001*** |
| Wv | 0.5 (0.06) | 0.56 (0.2) | 0.630 |
| Wh | 0.39 (0.04) | 0.24 (0.06) | < 0.001*** |
| R | 52.8 (6.04) | 41.8 (5.3) | < 0.001*** |
| %Cong | 22.6 (5.7) | 30.6 (9.8) | 0.015* |
| Rint | 55.6 (4.7) | 50.1 (9.8) | 0.010* |
| RiDSi | 3.04 (1.70) | 4.4 (2.2) | 0.075 |
| RiSS | 24.5 (1.42) | 21.5 (1.7) | < 0.001*** |
| RiDSf | 3.25 (1.73) | 4.5 (2.04) | 0.078 |
| RiS | 25.04 (1.18) | 19.7 (3.6) | < 0.001*** |

SD: Standard deviation, GH: Healthy Group, SG: Stroke Group, Wext: external mechanical work, Wv: Vertical work, Wh: horizontal external mechanical work, R: Recovery, %Cong: Congruity percentage, Rint: Instantaneous pendular re-conversion, RiDSi: Recovery initial double support, RiSS: Recovery single support, RiDSf: Recovery final double support, RiS: Recovery Swing. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

**Table 4**
Correlations between CoM energy transduction measures and spatiotemporal gait measures of participants in the study.

| Variable | HG Pearson's r (p value) (n = 15) | SG Pearson's r (p value) (n = 15) |
|---|---|---|
| Froude Number – R | 0.766** (0.001) | 0.794*** (0.001) |
| Rint – %Cong | −0.798*** (0.001) | −0.933*** (0.001) |
| Wext – Rint | −0.697** (0.004) | 0.293 (0.290) |
| Wv – Rint | 0.234 (0.402) | 0.308 (0.264) |
| Wh- Rint | −0.415 (0.124) | 0.458 (0.086) |
| SS% – RiSS | 0.047 (0.869) | −0.121 (0.667) |
| S – RiS | 0.406 (0.133) | 0.165 (0.558) |
| DSi % – RiDSi | −0.763*** (0.001) | 0.694** (0.004) |
| DSf – RiDSf | −0.689** (0.004) | 0.603* (0.017) |

GH: Healthy Group, SG: Stroke Group, R: Recovery, Rint: instantaneous pendular re-conversion, %Cong: congruity percentage, Wext: external mechanical work, Wv: vertical work, Wh: horizontal external mechanical work, SS: single support, S: swing, RiSS: Recovery single support, RiS: Recovery Swing, DSi: initial double support, RiDSi: Recovery initial double support, DSf: final double support, RiDSf: Recovery final double support.
* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

## 4. Discussion

In this study, spatiotemporal gait measures together with the CoM energy transduction were analysed using a novel approach at self-selected speed walking in a group of older patients with stroke. We set out to determine how Eh-Ev transduction changed throughout the different phases of the gait cycle and hypothesized that the $R_{int}$ values of each phase are likely deteriorated in stroke subjects in correspondence with spatiotemporal changes in those phases.

The walking speed adopted in the stroke group was two times lower than the healthy subjects in absolute terms and when considering the froude number. Although discussing this aspect is not one of the focuses of this work, it is essential to take this into account given that most of the studies presented in the literature use absolute speed values. Two absolute speed values do not necessarily reflect the same mechanical task, but if two people walk at the same Froude number then the actions are comparable. In this work analyzing self-selected speed, we are comparing what happens with a group that travels at a speed two times less than the other. Stroke survivors' walking speed was within the range described for this population (Ijmker et al., 2013), although that of the healthy group (Froude number = 0.42) were slightly smaller than the associated with optimal efficiency (Saibene & Minetti, 2003). The differences in the walking speed can be due to changes in step length, frequency of step or both (Saibene & Minetti, 2003; Willems et al., 2012). The latter was what we observed in this study when comparing the post-stroke subjects with the healthy ones, as reflected in the cadence and LC values found for each group.

The registered values for LC, LPr, LPnr and cadence, as well as the relative durations of the phases for the healthy group, are within the range of those reported in previous studies (Willems et al., 2012). As expected based on previous studies (Chen et al., 2005; Donelan, Kram, & Kuo, 2002b; Donelan et al., 2004; Mahon et al., 2015; Patterson et al., 2008; Perry & Burnfield, 2010), stroke survivors walked asymmetrically. Stride length was shorter with a prolonged swing phase of the paretic side, and LPnr was less than LPr. The support phase of both lower limbs occupied a large proportion of the walking cycle. The time of simple support of the unaffected limb was almost double that of simple support time with the affected limb. In accordance with (Goldie et al., 2001), the time of double support was higher than that of the healthy subjects in the situation in which the affected limb is behind the healthy limb, first pushing the CoM and then preparing for takeoff.

With respect to the pendulum-like determining variables, the values of Wext, Wv, Wh and R found were within the range previously described for healthy subjects (Saibene & Minetti, 2003; Willems et al., 2012) and post-stroke subjects (Detrembleur et al., 2000; Farris et al., 2015; Ramos Arim et al., 2017). The Wext value was significantly higher in the stroke subjects than the healthy group. It was not accompanied by a change in Wv value, as has been discussed for other populations with asymmetrical gait (van den Hecke et al., 2007). Changes in Wv have been associated with vertical displacement of CoM due to foot equinus, which is one of the characteristics in adults with hemiparesis (Detrembleur, Dierick, Stoquart, Chantraine, & Lejeune, 2003). However, the results of our study indicate that the most significant changes are in the temporal tuning of CoM energy observed continuously since the significant increase in Wext was accompanied by the rise in %Cong; this was notably higher in post-stroke subjects. Few applications of %Cong in humans are presented in the literature. These studies have established that %Cong reaches its minimum value when R is at its maximum (Gomenuka et al., 2016; Wilson, 2010). Given that %Cong is the result of the fluctuation of Eh and Ev over time, when these are predominantly out of phase their value is low, as observed in the control subjects. The high %Cong values observed in post-stroke subjects imply that Eh and Ev fluctuates in phase and the pendular mechanism alters, as reflected by the differences in the values of R and $R_{int.}$

In this work, additional information regarding the pendular mechanism of walking was obtained by analyzing the pendular transduction of the mechanical energy for each instant of time mean $R_{int}$. In post-stroke subjects, $R_{int}$ values were significantly lower than the values calculated for healthy subjects. Both R (Saibene & Minetti, 2003; Willems et al., 2012) and $R_{int}$ (Cavagna et al., 2002;

Gomenuka et al., 2016) depend on the speed since, in absolute terms (VM) and relative (Froude number). Part of this difference may respond to the asymmetries associated with pathology, the results of the energy recovered in the four phases facilitate the analysis of this factor. The accumulated energy values recovered in the four phases considered show that post-stroke subjects have their pendulum reconversion reduced in the two phases of single support (SS and S).

The effect seems to be greater when the supporting foot is that of the affected side (in this study, this corresponds to S). On the contrary, during both phases of double support (DSi and DSf), when one of the lower limbs pushes and the other brakes the body, although there are no significant differences between groups, the post-stroke subjects have a higher recovery of mechanical energy. This is an important point because, during the double support phases, mechanical work is required to redirect the CoM speed vector between the pendulum arcs of each limb (Donelan, Kram, & Kuo, 2002a; Soo & Donelan, 2012). This redirection comes from the net combination of actions of the trailing and leading limbs, and minimizing the total mechanical work is desirable to reduce metabolic cost (Donelan et al., 2002a; Kuo, Donelan, & Ruina, 2005). To establish the first level of discussion of the spatiotemporal gait parameters and the CoM energy transduction in the phases, a correlation between the duration and the energy recovered was evaluated. We did not find any association between the duration of the simple support phases and the energy recovered there. However, significant correlations were established during double support. Based on these results, it can be said that the mechanical energy recovered during transitions in healthy and post-stroke subjects follows a different trend with speed. In the first group, a shorter duration of the double support phase is associated with a minor loss of energy, while in the post-stroke subjects the opposite occurs. This can be significant to take into account during evaluations since a number of studies conducted with models have marked the importance of the mechanical work done in the transition phase rather than pendular motion itself as a significant determinant of the metabolic cost of walking (Donelan et al., 2002a).

Our analysis has some limitations, first an important methodological aspect need to be stressed. The force platform is the most accurate instrument for analyzes based on the trajectory of COM (Cavagna & Margaria, 1966). However, since in our study, we did not use a pre-set speed and we required the position of the CoM during several cycles, our option was calculate the position of the CoM by means of a 3D reconstruction. This implies a greater error than with a platform because the models used for the reconstruction of the movement require many assumptions although certainly is more accurate than using trunk movement as established for Zelik and Adamczyk (2016), particularly considering that the studied population presents asymmetric movements of its extremities. We tried to minimize the errors associated with this aspect, however it must always be considered that better models are possible. Moreover, external work does not represent the total work done, which also includes, among others, the internal work done to move limbs relative to the CoM (Saibene & Minetti, 2003; Willems et al., 2012). Its physiological relevance arises from the fact that performing reciprocal limb movements can result in no movement of the CoM. The asymmetries in the movement of the segments of the subjects with stroke could significantly affect the internal work. However, in this first study, we prefer not to quantify the internal work since a precise determination requires a high level of precision of the relative changes in velocity of each segment regarding the CoM. It can also be questioned whether the self-selected displacement used in this study is the best option; we anticipate considering this factor to make the results relevant in the context of daily functioning.

## 5. Conclusions

In addition to clinical examinations and gait observation, gait analysis provides useful information for treatment planning or surgical procedure selection. However, this information is largely based on the segmental kinematic; articular moment and electromyographic studies do not allow an analysis of the functionality of the action associated with the specific activities. In this study, when analyzing spatiotemporal gait measures together with the CoM energy transduction, we were able to reach two main conclusions:

- The alteration of the pendular mechanism in subjects post-stroke is mainly associated with fluctuations in Eh-Ev in phase.
- The mechanical energy recovered during double support phases in healthy and post-stroke subjects follows a different trend; in post-stroke subjects, a longer duration of the double support phase is associated with less energy loss with speed.

As the variables necessary to compute the CoM energy transduction in the different phases of the gait cycle are measured during the usual gait analysis, this evaluation required only additional calculations. We considered that the type of analysis performed in this work can facilitate a better understanding of how segmental impairs increase energetic demand, and so these values will be useful in clinical practice.

## Funding

This study was funded by Agencia Nacional de Investigación e Innovación (ANII), Uruguay, with funds from “Clemente Estable” modality II programs.

## Declaration of Competing Interest

None.

## Acknowledgments

The study was supported by ANII, Uruguay. The authors thank Dr. Pedro Gallardo for his collaboration in the selection and evaluation of the subjects, and Lic. Andres Rey and Lic. Mariana Carriquiry for their cooperation during data records. We also wish to express our gratitude to Dr. Carlo Biancardi and Dr. Leonardo Tartaruga for their kind suggestions.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.06.006.

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