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Complexity of human gait pattern at different ages assessed using multiscale entropy: From development to decline

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COMPLEXITY OF HUMAN GAIT PATTERN AT DIFFERENT AGES ASSESSED USING MULTISCALE ENTROPY: FROM DEVELOPMENT TO DECLINE

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Abstract

Multiscale entropy (MSE) has been applied in biomechanics to evaluate gait stability during human gait and was found to be a promising method for evaluating fall risk in elderly and/or pathologic subjects. The hypothesis of this work is that gait complexity is a relevant parameter of gait development during life, decreasing from immature to mature gait and then increasing again during old age. In order to verify this hypothesis, MSE was applied on trunk acceleration data collected during gait of subjects of different ages: toddlers at the onset of walking, pre-scholar and scholar children, adolescents, young adults, adults and elderlies. MSE was estimated by calculating Sample Entropy (SEN) on raw unfiltered data of L5 acceleration along the three axes, using values of τ ranging from 1 to 6. In addition, other performance parameters (cadence, stride time variability and harmonic ratio) were evaluated. The results followed the hypothesized trend when MSE was applied on the vertical and/or anteroposterior axis of trunk acceleration: an age effect was found and adult SEN values were significantly different from children ones. From young adults to elderlies a slight increase in SEN values was shown although not statistically significant. While performance gait parameters showed adolescent gait similar to the one of adults, SEN highlighted that their gait maturation is not complete yet. In conclusion, present results suggest that the complexity of gait, evaluated on the sagittal plane, can be used as a characterizing parameter of the maturation of gait control.

Keywords:

Multiscale Entropy; human gait; gait maturation

Introduction

Multiscale entropy (MSE) has been introduced to quantify the complexity (sample entropy, SEN) of a time series on multiple spatio-temporal scales [1]. In biomechanics, MSE and/or SEN have been applied to evaluate stability during human gait and were found to be promising quantitative methods for evaluating fall risk in elderly and/or pathologic subjects [2–4].

Leverick et al [4] found that SEN measures experienced statistically significant increases in response to increasing age and gait impairment caused by cognitive interference on healthy adults and elderlies: they concluded suggesting that entropy appears to be a viable candidate for assessing the stability of human locomotion. In a previous work, Bisi et al [2] evaluated the performance of different gait stability indices on young adults and toddlers at the onset of walking (toddlers were assumed as individuals whose gait is a-priori unstable) and found that SEN was able to differentiate between unstable toddlers and stable healthy individuals.

The aim of the present study is to apply MSE to characterize the complexity and the development of human gait during a life span.

The onset of independent gait in children starts generally around age 1: the first 6 months of independent walking represent a process of integration of postural constraints into the dynamic mobility requirements during gait, after this period, a tuning phase begins, characterized by a more precise adjustment of gait parameters [5]. As children grow older, their gait pattern begins to approximate more closely that of an adult: by age 3-4, most of the adult kinematic patterns are present [6], however gait maturation continues.

In the literature, there is no common agreement regarding the age at which gait maturation is achieved. Some works refer to ages between 5 and 7 [6–8], indicating that changes after this age are more likely to be influenced by changes in height than by age. Other investigators [9–12] indicate that gait pattern continues to develop until adolescence or that the age of gait maturation is higher

than 8. When gait maturation is achieved, mature gait remains steady during adult life until some deteriorations occur during ageing: gait performance decreases showing different changes in gait parameters and/or segmental kinematic patterns that are usually specific for different pathologies [13].

The hypothesis of the present work is that the complexity of gait could be a relevant descriptive parameter of these changes, decreasing from immature to mature gait and then increasing again during old age. The identification of a robust and sensitive indicator of gait complexity, able to describe the process of maturation during growth and to highlight possible deteriorations during the aging process, would be useful for both understanding and monitoring gait pattern maturation/deterioration during life.

In order to preliminary explore and verify the validity of this hypothesis, MSE was applied on trunk acceleration data, collected during gait in ten groups of subjects of different ages: from toddlers to elderlies. MSE was applied separately to the anteroposterior (AP), vertical (V) and mediolateral (ML) direction of the collected trunk acceleration. Participants were asked to walk at self-selected speed in a corridor: the choice to analysed gait at self-selected speed was guided i) by the necessity not to influence the spontaneous control of gait and ii) by knowing that imposing velocity, participants could alter their biomechanics in different uncontrolled ways (e.g. by changing stride length and/or cadence) [14]. In order to support the interpretation of MSE results as a characterizing aspect of gait maturation, other parameters of gait performance were evaluated: smoothness, variability of stride time and cadence.

Materials and methods

Study subjects

Ten groups of participants of different ages were included in the study. Group details are described in table 1.

TABLE 1 HERE

All of the children had no known developmental delays. All children and adults had no musculoskeletal pathology.

The Review Board Committee of the authors' institution approved this study, and informed consent was obtained from the participants' parents for children and from adult participants.

Experimental setup

Two tri-axial wireless inertial sensors (OPALS, Apdm, USA) were mounted respectively on the lower back and on the right leg using straps.

Measures of accelerations of the trunk and of the right leg were recorded at 128Hz. The participants were asked to walk at self-selected speed in a corridor. Tests were performed in kindergartens for toddlers, schools for children and adolescents, gait analysis laboratory for adults and care homes for elderlies. The selected corridors were always longer than 12 m. The procedures for collecting and selecting data on toddlers were the same as presented in [2].

Data analysis

Stride detection was estimated from the angular velocity around the medio-lateral axis of the lower leg [15]. The first two and last two strides of each test were excluded from the analysis in order to exclude gait initiation and termination phases. For all the participants 10 consecutive strides were analysed: 14 was the maximum number of strides obtained in the less experienced infants. Each time series data included a number of data points between 1000 and 1500 [1,16]. Cadence (Cad) was calculated for each participant as the median values obtained on the 10 strides. Stride-time variability [2] (STv) was estimated as the standard deviation of the stride time, for each participant.

No additional filtering procedure was applied on collected data to assure that information was not lost or altered due to filtering. Matlab R2009b (MathWorks BV, USA) was used for data and statistical analysis.

SEN was calculated applying the method on the V, AP and ML accelerations of the trunk (SEN_v, SEN_{ap} and SEN_{ml}). Values of τ were ranged from 1 to 6, and m and r were fixed respectively at 2 and 0.2, as suggested by Pincus [17] and later applied by Richman and Moorman to biological time series [18].

Gait smoothness was estimated through the harmonic ratio (HR) [19] of L5 acceleration signals applying the method on the V, AP and ML axis (HR_v, HR_{ap} and HR_{ml}).

A Jarque-Bera test [20] was performed to test normal distributions of the estimated parameters on the different groups: since the normal distribution was not verified on all the groups, median values and 25- and 75- percentiles of results were calculated.

A Kruskal-Wallis test [21,22] with minimum level of significance of 5% was performed to analyse the effect of age on SEN, Cad, ST_v and HR. When age effect was found, a multiple comparison test [23] was performed to evaluate which were the analysed ages showing significantly different results from the 27YA group (confidence level fixed at 95%). Dunn-Sidak correction was considered for post-hoc analysis [24].

The potential influence between Cad and SEN was evaluated: Pearson correlation coefficients (ρ) between SEN along the three axes and Cad were calculated both per single age group and on all the collected data.

Results

SEN_{ap} and SEN_v followed in general the hypothesized trend from toddlers to adults, showing median values decreasing with increasing group age: the differences among the groups increased

with τ . SEN values for the group of adolescents did not follow the constant decrease and showed values close to (SEN_{AP}) or higher than (SEN_V) the 10YC group. Starting from the group of 45YA there is a general increase in SEN values both on the AP and the V axis. The Kruska-Wallis test on SEN_{AP}/SEN_V showed a significant effect of age on the complexity of the gait acceleration signal, along the AP/V axis respectively, if $\tau \geq 3$ ($p=0.001$): the significance of the test increased with increasing τ ($p<0.0001$ for $\tau=6$). The multiple comparison test on SEN_{AP} showed that the mean ranks of toddlers and young children (T2wks, T6mo, 4YC and 6YC) were significantly different from those of 27YA when $\tau=6$; adolescents' SEN_{AP} values (15YA) were close to the ones of 10YC and higher than adults'. The multiple comparison test on SEN_V showed that the mean ranks of toddlers, young children (T2wks, T6mo, 4YC and 6YC) and adolescents were significantly different from those of 27YA when $\tau=6$; adolescents' SEN_V values (15YA) were higher than 10YC children and adults.

No expected trend among groups of different ages was found on SEN_{ML}. SEN_{ML} increased with τ , with median values between 1.49 and 1.87 for $\tau=6$. T2wks and 4YC groups showed SEN_{ML} close to the one of adults and elderlies, while T6mo, 6YC, 10YC and 15YA groups higher ones. The Kruska-Wallis test on SEN_{ML} showed no significant effect of age on the complexity of the acceleration signal along the ML axis.

In general, SEN, calculated with $\tau=1$, performed similarly (values close to 0.5) when applied on different populations and on the three axes (AP, V and ML). With increasing values of τ , SEN showed higher and higher values, differentiating populations. Table 2 shows median SEN (and 25th - 75th percentiles) when calculated on the three directions using $\tau=6$.

SEN median values (and 25- and 75th percentiles) are shown in Figure 1a and b respectively for the AP and V. The six subplots of each figure show SEN obtained with different values of τ and asterisks indicate significant differences from the 27YA group.

TABLE 2 HERE

FIGURE 1a and b HERE

Cad showed a constant decrease from T6mo to 15YA and then constant values for the groups of adults and elderlies. STv show a constant decrease from T2wks to 10YC, then remained constant and showed a slight increase in the 85YA group. HR showed an increase from childhood to adulthood (from T2wks to 10YC) and a decrease during old age. The Kruska-Wallis test showed a significant effect of age on Cad, STv and HR along the three axis. Figure 2 shows median results of Cad and STv; Figure 3 respectively of HRv, HRml and HRap (asterisks indicate significant differences from the 27YA group).

FIGURE 2 HERE

FIGURE 3 HERE

Correlation coefficients (ρ) between Cad and SEN showed the maximum values when calculated on all the data and for $\tau=6$: $\rho=0.43$, 0.48 and 0 respectively for the AP, V and ML axis.

Discussion

MSE was applied on trunk acceleration data collected during gait of subjects of different ages in order to evaluate whether the complexity of gait could be a relevant parameter of gait control maturation, decreasing from immature to mature gait and then increasing again during old age. In addition, to provide a complete observation of gait performance during the life span, Cad, STv and HR were evaluated. The results of this study confirmed in general the expected trend. Complexity of the acceleration signal along the sagittal plane showed a significant effect of age and could discern between immature and mature gait. A slight increase starting from 25YA to 85YA was found even though the differences were not statistically significant. Interestingly, adolescent results

1 did not follow the decreasing trend from immature to mature gait, highlighting aspects that could
2 not be observed by looking at classical gait spatiotemporal parameters as cadence or gait speed [25].
3
4 SEN values decreased from toddlers to 10YC but then remained constant (SEN_{ap}) or increased
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6 (SEN_v) in the group of adolescents. In contrast, HR, Cad and ST_v of 15YA were similar to the ones
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8 of 27YA. This phenomenon could be explained by considering the peculiar period they are
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10 experiencing: a transition from childhood to adulthood that involves biological, cognitive and socio-
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12 emotional changes [25].
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17 Study results are in agreement with literature [2–4] supporting that MSE, when applied in
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19 biomechanics on trunk acceleration data collected during gait, can highlight differences in
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21 complexity between healthy adults, elderlies and toddlers, indicating a possible risk of falling. On
22
23 the other hand, when analysing gait of 6 to 15 year old participants, it is difficult to argue that the
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25 increased complexity is related to the risk of falling, given that at that age it is uncommon to see
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27 unexpected falls during level walking. Thus, a better understanding is necessary of the possible
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29 meaning of SEN when applied on the trunk acceleration signal during gait.
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35 Apparently, some characteristics in gait dynamics are similar in children and elderly individuals:
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37 they both show an increase in stride time variability and a decreased performance (lower HR) when
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39 compared to young adults. On the other hand, we know that changes in gait of older persons do not
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41 simply reflect a return to an immature gait pattern [26]. Immature gait dynamics in children may
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43 reflect the subtle, ongoing development of more than one component of motor control, like
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45 biomechanical and neural properties (e.g. electromyogram recruitment patterns) [26]. After the age
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47 of 40-50 [27,28], there are other different modifications in factors affecting gait performance: age-
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49 related degradation of joints (e.g. articular cartilage and bone epiphysis), loss of skeletal muscle
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51 strength and decline in vision, reaction time, peripheral and vestibular sensations [28].
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57 It could be argued that SEN results are related to the level of automaticity with which gait is
58
59 controlled: small SEN values (low complexity) are indeed associated with high regularity. Lamoth
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et al (2011) [6] found that during dual tasking SEN showed larger values in elderly individuals indicating that changes in cognitive functions contribute to changes in gait complexity and automaticity.

If this is true, present findings suggest that children, as could be expected, have still to learn, explore and create neuronal networks for walking, and adolescents have a not yet mature automaticity of gait and require high cognitive attention when compared to young adults. Future research will have to focus on examining gait during single and dual task condition in order to investigate if MSE can be an index of the amount of cognitive input during walking.

No effect of age and/or maturation has been found on SEN when calculated on the trunk ML acceleration: this could suggest that the most relevant aspects of gait maturation are shown on the sagittal plane (dimension of progression). These results are in agreement with what was previously shown by Lamoth et al [29]: a larger SEN indicated a decreased regularity and during dual tasking in elderly, SEN showed larger values in the AP and not in the ML direction. Also by looking at single task gait, their results agree with the present ones, not showing significant differences in the AP direction: no comparison can be done on the V axis because they only analysed AP and ML directions.

From a more specific and technical point of view, present results suggest that, in order to correctly characterize gait development, τ higher than 4 must be considered and that characterization capacity increases with τ , in agreement with the literature [2,3]. τ higher than 4 means that frequencies below 10-16Hz contribute the most in characterizing the automaticity of human gait at different ages. In fact, operating four coarse graining procedures on gait acceleration signal would filter frequencies higher than 16 Hz, while operating five or six would filter frequencies higher than 13 Hz or 11 Hz respectively.

An aspect to be considered is the possible influence of the different participants' cadence on SEN results: participants were asked to walk at self-selected speed in order not to influence the

spontaneous control of gait. By looking at Cad results, there is a clear decrease in absolute cadence from T6mo to 15YA: on the other hand, the results of 15 YA showed high values of SEN that cannot be related only to the values of cadence. Correlation results showed that there is a moderate correlation between cadence and SEN ($\tau=6$) on the sagittal plane: AP and V accelerations are closely related to forward propulsion and thus more sensitive to cadence differences than ML accelerations. However, the correlation is only moderate and the shown SEN trend cannot be completely due to the differences in cadence. More research is needed in this direction to establish how cadence and/or velocity influence the estimation of MSE.

The present findings followed the hypothesis that higher complexity is associated with immature gait, which can appear to be in contrast with some other literature results. Toghici et al (2012) [16] e.g. associated higher entropy with better health: this difference could be due to the different placement of the sensor (in their study the sensor was placed on the leg) because it is known that results of nonlinear time series analysis of gait accelerations strongly depend on sensor placement [30].

One possible limitation of this preliminary study is the limited number of strides analysed (10), due to both low walking experience and lack of cooperation in toddlers. Literature shows that 10 strides are sufficient for reaching a MSE steady value [16,31]. Moreover, the analysed signals included always more than 750 data points and from the literature it is suggested that SEN is largely independent of the time series length when the total number of data points is larger than 750 [1]. The sampling frequency used was 128Hz, thus, the values of selected τ have an influence on the aspects of complexity and on the frequency contents analysed by SEN, as described above.

When estimating HR and STv, the reliability of these indices on 10 strides is not high (they reach a 20-30% threshold of the percent interquartile range/median ratio [31]). However, the aim of this work was not to reach an individual assessment, for which a higher number of strides would be required, but to evaluate trends on group results for supporting the characterization of gait at

different ages. In conclusion, the results of this exploratory study suggest that the complexity of gait on the sagittal plane can be an innovative and relevant parameter for characterizing the maturation of gait, allowing highlighting new insight in motor maturation. Complexity of adolescent gait is high when compared to adults and to younger participants (10YC), suggesting that the physical and cognitive changes they are experiencing contribute markedly to motor development [32] and that complete gait maturation is reached later. More research is necessary in order to analyse the development of motor control during this period of transition with particular focus on the influence that adolescence changes have on motor performance.

Further work will be addressed to evaluate whether MSE is a robust and sensitive method for characterizing maturity and if it is related to gait automaticity: the identification of such a method may contribute to our understanding of the development of the control of gait.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Table1

Abbreviation	Group description	age	weight (kg)	height (cm)
T2wks	10 toddlers at two weeks of walking experience	13±2months	10±1*	78±3*
T6mo	10 toddlers at 6 months of walking experience	13±2months	10±2*	77±3*
4YC	10 4-year old children	4±0 years	17±2	104±4
6YC	10 6-year old children	6±0 years	23±1	121±2
10YC	10 10-year old children	10±0 years	40±5	145±8
15YA	10 15-year old adolescents	15±0 years	61±11	164±6
27YA	10 27-year old adults	27±1 years	67±14	171±9
45YA	10 45-year old adults	45±2 years	71±15	172±10
65YA	10 65-year old adults	67±2 years	83±15	173±6
85YA	10 85-year old elderlies	84±2 years	75±10	168±7

Table 1. Details of age groups participating in the study. * Weight and height of toddlers were measured at 12 months. Data from groups T6mo and 27YA were already presented in Bisi et al [2].

Table 2

	MSE $\tau=6$								
	AP			V			ML		
	median	25th pctl	75th pctl	median	25th pctl	75th pctl	median	25th pctl	75th pctl
T2wks	1.50	1.45	1.55	1.67	1.35	1.81	1.55	1.39	1.67
T6mo	1.53	1.26	1.66	1.70	1.50	1.77	1.87	1.60	2.02
4YC	1.46	1.29	1.54	1.44	1.27	1.68	1.61	1.55	1.67
6YC	1.37	1.16	1.64	1.28	1.20	1.44	1.77	1.65	1.88
10YC	1.11	1.05	1.22	1.18	1.14	1.30	1.87	1.70	1.97
15YA	1.13	1.06	1.30	1.37	1.36	1.42	1.84	1.61	2.00
25YA	0.90	0.79	0.97	0.99	0.86	1.06	1.49	1.44	1.62
45YA	0.97	0.74	1.16	1.03	0.95	1.18	1.68	1.54	1.94
65YA	1.08	0.76	1.23	1.07	0.98	1.15	1.66	1.55	1.83
85YA	1.07	0.90	1.20	1.19	0.96	1.38	1.70	1.67	1.76

Table 2. SEN (median, 27th and 75th percentiles) for the different age groups calculated using $\tau=6$.

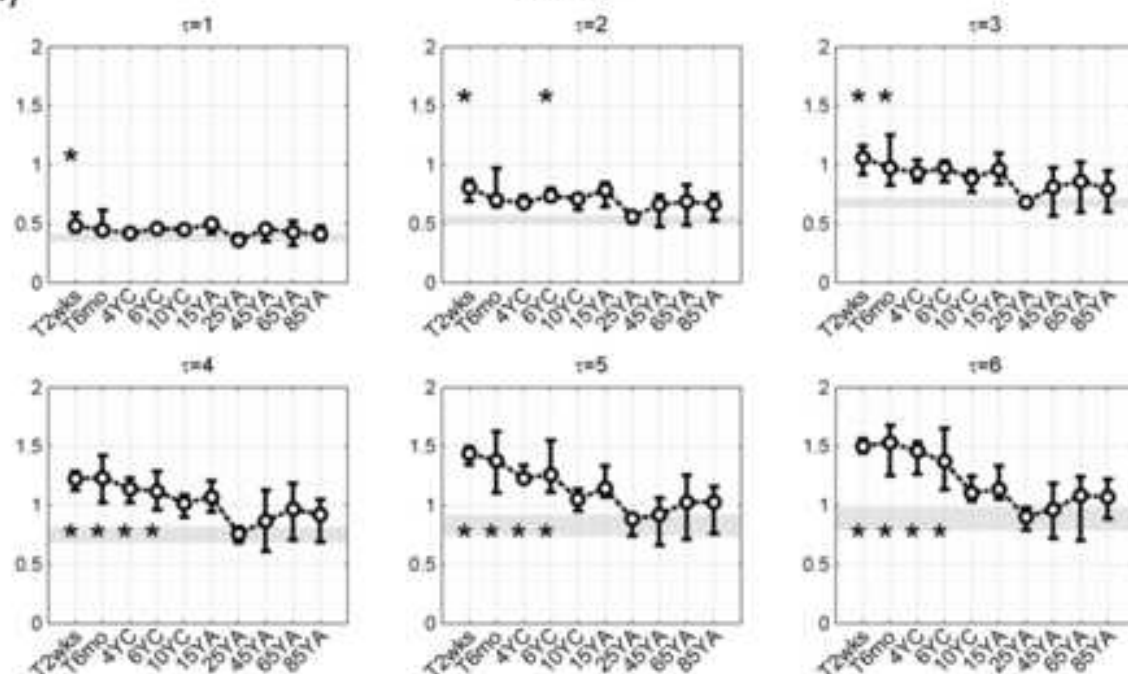
Figure 1. a) SENap and b) SENv (median, 27th and 75th percentiles) for the different age groups, obtained with different values of τ . Grey band indicates 27YA SEN value range; asterisks show significant differences from the 27YA group.

Figure 2. Cad (median, 27th and 75th percentiles), (stride/sec) and STv for the different age groups. Grey band indicates 27YA value ranges; asterisks show significant differences from the 27YA group.

Figure 3. HRv, HRml and HRap (median, 27th and 75th percentiles) for the different age groups. Grey band indicates 27YA value ranges; asterisks show significant differences from the 27YA group.

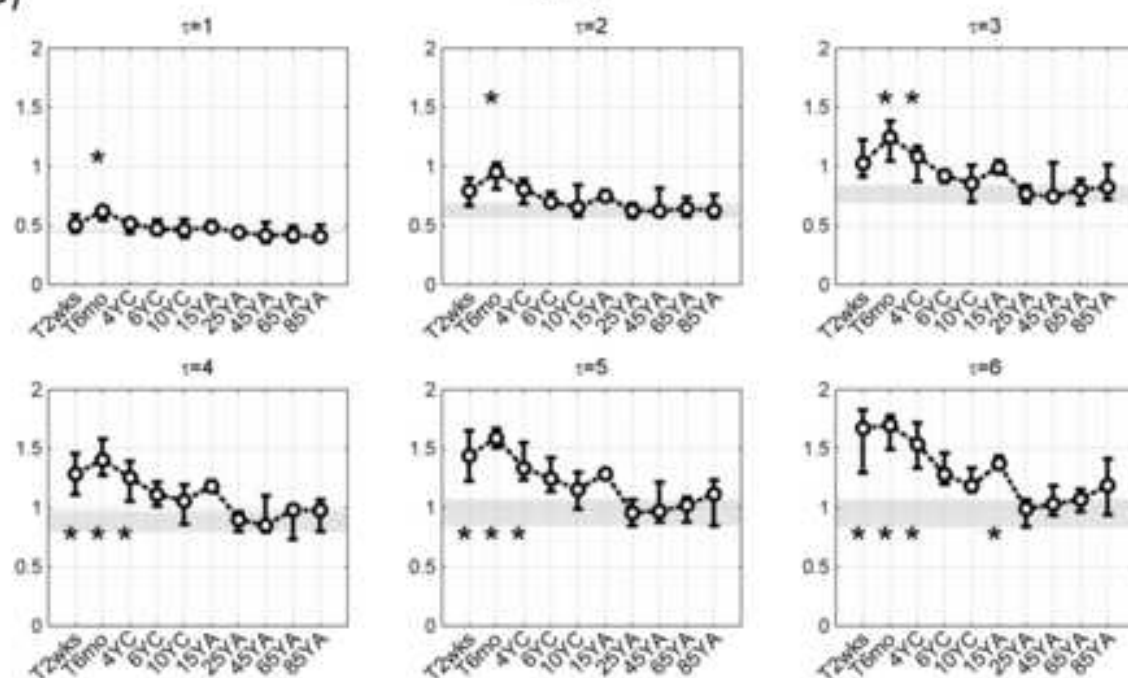
a)

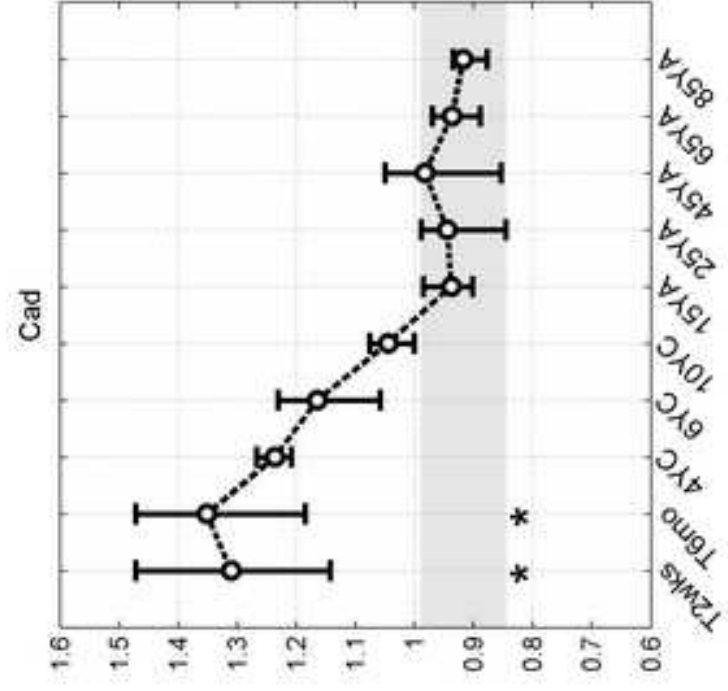
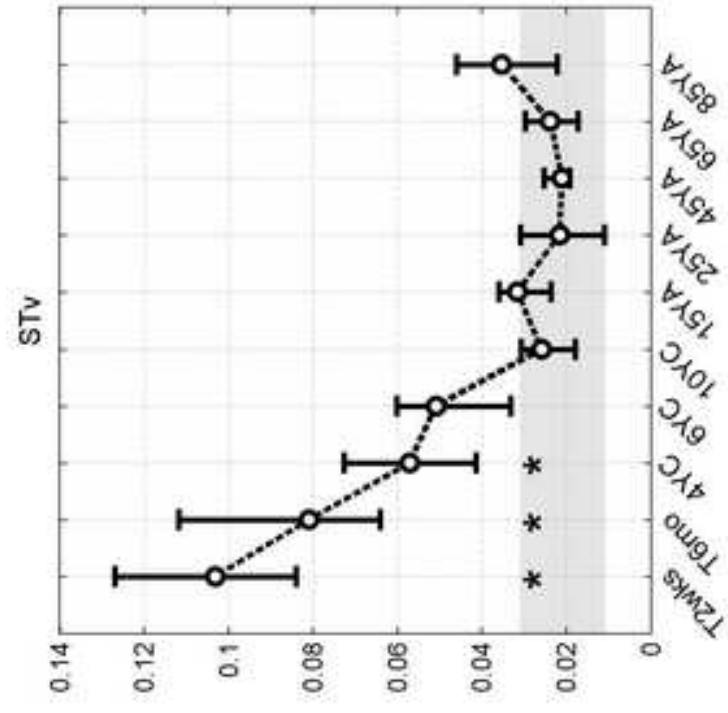
SENap

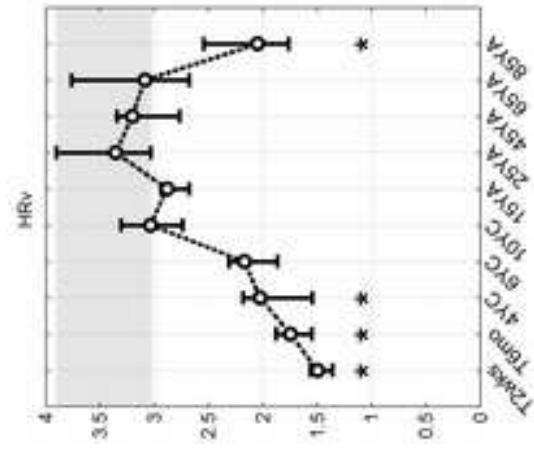
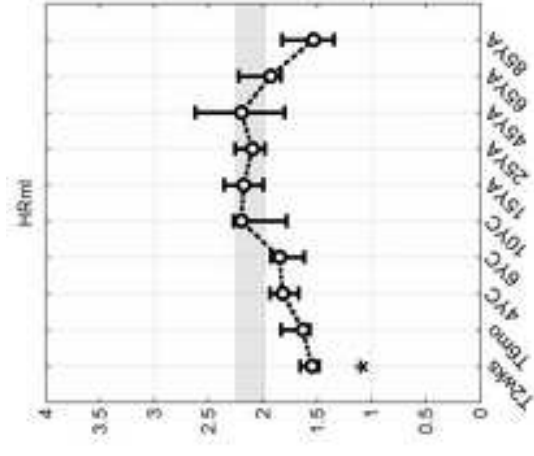
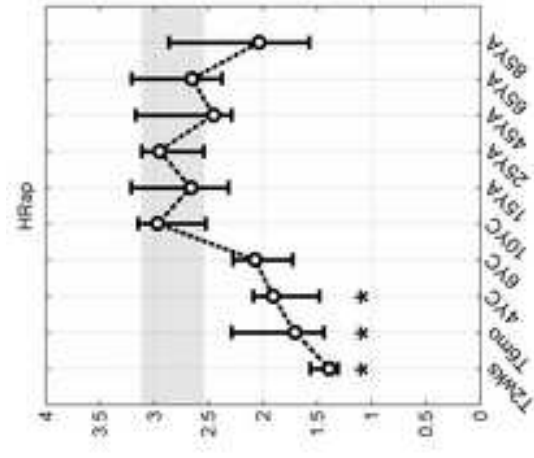


b)

SENv







Research highlights

Gait complexity could be a characterizing parameter of gait development during life.

10 groups of different ages participated in the study: from toddlers to elderlies.

Multiscale entropy was applied on trunk acceleration data collected during gait.

On sagittal plane, MSE lowered with maturation showing adolescents as not yet mature.

Young adults showed the lowest MSE levels.