# An Evaluation Method of Complex Movement and Dynamic Stability of the Arm During Walking Based on Gyroscope Data

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***Abstract*—The work introduces a new means for quantification of dynamic stability and upper limb movement as a whole during gait. Swinging arms during gait performed by the experiment volunteers, as a cyclic motion, was quantified using two parameters AH (the convex hull area) and already known to the medical community - ROM (range of motion) revealed a potential use of the former in the scientific community. Looking at the results of the two parameters, even though ROM has shown to seem to be comparably instrumental as it yielded surprisingly rather identical results to the AH parameter (which yielded values of subjects walking at 5 km/h about twofold larger than those in volunteers walking at 3 km/h), it still fails to examine the pair of angles at the same time due to a strong interrelation of the observed joints in volunteers. As complex upper limb movement appears to be rather uniform for both arms, no significant differences between the dominant and non-dominant arm were found. It appears that the novel method using inexpensive gyroscopes is capable of quantifying dynamic stability and periodic movement pattern of the upper limb, therefore a pair of two common gyroscopes or goniometers placed on the patients body may find their place among standard equipment for clinical examinations or in the field of biomechanical measurements. The presented method might possibly also become a part of MoCap systems or in the area of prosthetics in which dynamic stability or movement patterns are key parameters.**

***Keywords*—alngles; convex hull; dynamic stability; gait; gyroscope; joint***

## I. INTRODUCTION

The area of movement pattern quantification during gait for upper limb nowadays recognizes several methods which are commonly used to study it, recently the most notorious among the members of clinical community being the phase analysis method [1], [2]. Methods relying on cyclograms (or cyclokinograms basically so called angle-angle diagrams) are used to examine periodic movement patterns of the upper extremity [3], [4], [5]. To take a closer look at the observed movement, these diagrams are formed by plotting a pair of joint angles which are otherwise plain clear and objective [5], [6]. When it comes to the issue of stability if talking about human gait, one comes across rather a number of various definitions, each evolving from a different area of practice. Focusing more specifically, the definition of the dynamic stability describes the potential to keep a steady pace by accommodating small perturbations that occur naturally during walking [7]. This particular type of stability following the definition is however a realm which is only being researched, still lacking the proper potential use which the invented methods for its quantification may find. The most widely used method for this purpose relies on local dynamic stability focused on whether or not may small perturbations cause the system to drift away from its state [8]. This contradicts the premise of global stability which states whether a system is capable of sustaining any volume of perturbation. Therefore, to evaluate and consider the stability of a whole system (e.g. upper limbs), one needs to take into consideration courses of multiple variables, which is a requirement angle-angle diagrams are not capable of meeting.

The angle-angle diagram presenting parameters of trajectory plot relies on a number of calculation techniques, nevertheless it is desirable (and not always the case) for a technique to present us with an assessment of the possibility of the upper limb on a particular trajectory perturbing onto its close alternative, or if it would or would not converge back to the initial one. Taking periodic movements into consideration, there is a likely probability of the system to get back to its obvious pattern following a perturbation, described by so called orbital stability. Talking about periodic movement patterns, the basic parameters describing the geometric parameters include also area within the angle-angle diagram, [9]. This area has been quantified in previous works using the method based on the shape of the envelope (convex hull)

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[10], [11], the main focus being first and foremost stability evaluation [12], [13], [14]. Moreover, the method allowed for quantification of the two body joint angles interdependence when walking. Using the data on the mentioned variables course provided for evaluation of the range of upper limb movement complexity in sagittal plane. Elbow joint angle and shoulder joint angle excursions as plotted on an x-y plot thus define the shape of the convex hull as the smallest convex region enclosing a set of points in 2-D space. The concept of the area of the convex hull (AH) [15], although an established method among biomechanics researchers (some software of MoCap systems allow the calculation of this area; e.g., SwayStar manufactured by Balance International Innovations GmbH), has yet failed to find use in the research of complex upper limb movement as a whole and dynamic stability of entire upper limb during gait.

Therefore, the main purpose of this paper aims to present the use of the AH in the upper limb movement quantification, dynamic stability during gait, and setting the assumed values of the AH in healthy subjects. Proceeding from this premise, another aim of the work is to point out to the possible use of the new parameter in areas in which MoCap systems set of two sensors (goniometers or 1D gyroscopes), recently a rather popular choice in the field of medicine and rehabilitation, are capable of only monitoring two angles. The concept of AH may as well find use in the research of arm movements during walking using vastly inexpensive (single or two axis) gyroscopes commonly find in mobiles and watches. It has been realized that, the method relying on data assessment using gyroscope system may reveal new ininsights on balance deficits [16], [17]. Even so, AH method still fails to find use for the purposes of gyroscope data evaluation in measurement of shoulder angle and the elbow angle during gait. The final impulse to test the new method is the fact that standardized parameters, such as standard deviations of displacement, appear lacking sufficient transparency since they are not correlated to any of the trajectory parameters [18], which directly reflect the measured body segment movement [19] among which there are specific movements such as tremors caused by tiredness or illness. The desired objective of this article is therefore the introduction and presentation of new methods based on AH, verification of the potential and accurateness of the new parameter and the comparison of the discussed parameter with the traditional parameter, possibly based on range of motion (ROM) of joint [20]. The designed test procedure consisted in an analysis of a non-complex cyclic movement of swinging both arms in subjects performing gait and following determination of future use possibilities.

## II. METHODS

### A. Test Procedure and Participants

A set of ten healthy volunteers (HVs) (aged 22 (SD 0.5), weight 71 (SD 12) kg, height 176 (SD 8) cm) from among students of Czech Technical University in Prague participated in the study were selected within a single day on a random selection basis. The dominance of either arm was decided using the Edinburgh Handedness test [21] prior to recording arm motion, which identified one weak left hander (-9%) and nine right handers (from 11% to 100%), resulting in overall handedness of 49% (SD 31%). During HVs task to undergo a treadmill walk in 80 second series with 2 minute breaks between each take. Each measurement was shortened by cutting off the initial and final 5 gait cycles to exclude the inertial phases, and thus shortened to a total record length of 60 seconds recorded with a sample frequency of 100 Hz. Despite human capability to walk at speeds ranging from 0 km/h to about 9 km/h, the two walking speeds decided for the study of the values quantifying the arm movement were 5 km/h and 3 km/h. The former value has been selected for being somewhat normal speed we commonly walk unless any factors interfere [22], [23] and the latter was the supposed slower speed which recovering patients would choose to walk [24].

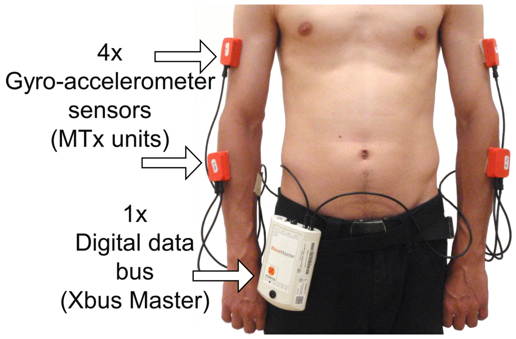

Figure 1. Set-up of the Xsens system including set of four gyro-accelerometer sensors monitoring body segments anatomical angles.

### B. Motion Capture Equipment and Data Processing

The technical equipment measuring upper limbs segment movements consisted of an Xbus Kit system (Xsens Technologies B.V.) representing a light (330 g) and portable MoCap (motion capture) design employing miniature MTx units (dimensions 38x53x21 mm) measuring body segments movements with drift-free 3D orientation (Fig. 1), and a computer (laptop HP Compaq 6735s with AMD Turion X2 dual core processor and Windows 7 operating system) using MT Manager software (Xsens Technologies B.V.). Calibration of MTx units took place prior to each measurement, resulting in its setting of one axis of

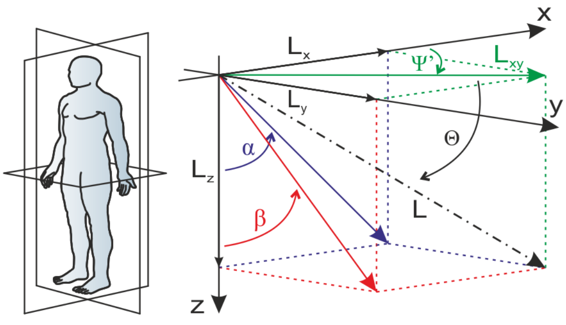

Figure 2. Observed Euler angels and the bodys anatomical coordinate system angles.

the coordinate system being collateral to the anterior-posterior axis (rear-front line) of the treadmill with the measured subjects, and other two axes being perpendicular to the anterior-posterior axis taking gravitational force into consideration. After the adjustment, MTx units were mounted on HV's upper extremities according to [25], and at the same time in accordance with the MoCap system manufacturer recommendation as well [26]. Four MTx units located on dorsal sides of upper arms and forearms close to centers of mass of segments were then fully prepared for the experiment, without any restriction of upper extremities or trunk motion.

Pitch ($\Theta$) and yaw ($\Psi$) angles were quantified by MTx units [28], [29]. In order to calculate rotational motion of a segment around medial-lateral axis of the anatomical coordinate frame of the human body, the three Euler angles were selected. Sagittal plane rotations (following $\alpha$ angle, see Fig. 2) revolve around the medial-lateral axis (y), frontal plane rotations (following  angle) revolve around the anterior-posterior axis (x) and transverse plane rotations (following $\Psi$ angle) revolve around the superior-inferior axis (z). Fig. 2 illustrates the process of flexion/extension angle quantification taking place within the medial-lateral axis (the sagittal plane). Within the Cartesian coordinate system, lets take an example of a segment of length L, Fig. 2. Following formula defines segments projection lengths onto planes:

$$L_x = cos(\Psi') \cdot cos\Theta \cdot L \tag{1}$$

$$L_z = sin\Theta \cdot L \tag{2}$$

proceeding that angle $\Psi' = \Psi_0 - \Psi$, or the difference between angle $\Psi_0$ yielded by the MTx unit calibration process and $\Psi$ representing a yaw angle value provided by MTx unit during the actual experiment. The resulting flexion/extension angle in the sagittal plane ($\alpha$) represents:

$$\begin{aligned} \alpha &= arctg\left(\frac{L_x}{L_z}\right) \\ &= arctg\left(\frac{L.cos(\Psi').cos(\Theta)}{L.sin(\Theta)}\right) \\ &= arctg(cos(\Psi').cotg(\Theta)). \end{aligned} \tag{3}$$

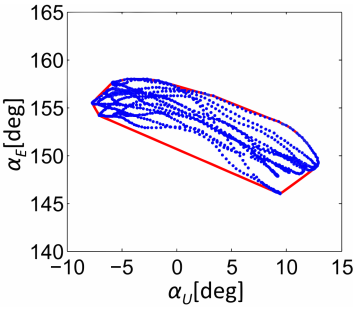

Figure 3. Cyclogram and convex hull of points. Results calculated by plotting shoulder ( $\alpha_U$) and elbow joint ($\alpha_E$) angles vs. each other (record length 10s; walking speed 3km/h; dominant upper limb of HV).

The presented formula defines upper arm and forearm angles in the anatomical coordinate system during gait. These however can not be considered joint angles due to their relativity to the x and z axis. Utilizing the data obtained by the MTx units placed on the described body segments and their application to the formula yields values of the forearm angle ($\alpha_F$) and upper arm angle ($\alpha_U$) in the sagittal plane. The $\alpha_U$ angle is shoulder joint angle relative to the vertical z axis. The elbow joint angle $\alpha_E$, i.e. plantar flexion/extension angle is calculated as $\alpha_U - \alpha_F$.

### *C. Methods of Quantification of Upper Limb Movements*

The convex hull, a well-known mathematical tool used in posturography, serves as a basis for a new method of upper limb movement quantification. The biomechanics community recognizes the importance of the shape of the convex hull [12], [13], [14]. The convex hull can be characterized and defined by the shape of its area. This shape is characteristic and it has been used to measure center-of-pressure (CoP) displacements and the evaluation of stability by using a force platform [15]. The evaluation of postural stability of trunk by gyro/accelerometer systems has mentioned the AH [19], [27]. The area, in our instance, is defined by the envelope (i.e. convex hull) of two joint angles, namely of the shoulder joint angle and elbow joint angle excursion, where the variables are plotted on an x-y plot (Fig. 3). The physical unit used for AH is deg$^2$ . The convex hull computation in MatLab (MatLab R2010b, Mathworks, Inc., Natick, MA, USA) used the Delaunay triangulation, which is a particular way of joining a set of points in a triangular mesh. The mentioned triangulation is described in detail by Cignoni et al. [30] and Preparata et al. [31]. The software, which is based on the MatLab software functions, calculates the AH of the plots of points of the shoulder joint angle points and elbow joint angle plots. The length of the dataset (60s) and the sample frequency (100 Hz) determine the number of points. The smallest convex region surrounding all points in the set is the set of points in 2-D space and the method of finding the triangular mesh is used to solve the problem of the convex hull set of points. The ROM is defined as the difference between the maximum and minimum joint angle and the ROM of each joint is used as a method to evaluate the upper limb movements [20]. It can be used to calculate cases like cyclic patterns of body movements, i. e. walking. For this study, a custom-designed program based on functions of MatLab was used to calculate the ROMs in the elbow and shoulder joints of dominant and non-dominant upper limbs of each HV. The analysis involved the determination of the joints in sagittal plane.

### *D. Statistical Analysis*

The data were divided into two sets. The calculation involved both quantitative parameters (ROM and AH). First group included data measured on the dominant upper limb and the second group contained data measured on the non-dominant upper limb. The data sets were furthermore divided into subsets, taking into consideration the speed of walking. The HVs were walking at two speeds 3km/h and 5 km/h on a treadmill. To test the normal distributions of the parameters, the Jarque-Bera test was applied in the subsets. The comparison of the results included the following values - the median (Mdn), minimum (Min), maximum (Max) and the first (Q1) and third (Q3) quartile. The second test, the Wilcoxon test, was used to assess the significance of the differences. The compared data included the differences between the data and measurements by MTx units placed on dominant and non-dominant upper limb; differences of measurements of HVs walked at the two set speeds- 3 km/h and 5 km/h on a treadmill. A value of $p<0.05$ was set for the significance level

To study the differences and relations between the AH and ROM and the differences between the body height and parameters, the Spearmans rank correlation coefficient had to be calculated. It was calculated between the data subsets. The strength of the correlation between the estimated values and the observed values can be verbally described as the correlation in an effect size. The absolute value can be described with the following guide: 0.00-0.19 (negligible), 0.20-0.39 (weak), 0.40-0.59 (moderate), 0.60-0.79 (strong) and 0.80-1.0 (very strong). MatLab software was used for the statistical analysis.

## III. RESULTS

Following the calculation of the value for every required AH and ROM from every experiment, these underwent statistical analysis in the MatLab software to uncover possible relations between the AH and ROM obtained under different conditions (speed), from individual subjects, or respective limbs. Fig. 4 uses a plot to illustrate the Mdn, Min, Max, Q1 and Q3 for the calculated values of AH and ROM (Tab. I). The normal data distribution condition was decided using Jarque-Bera test. As it followed, Due to the fact that AH failed to prove normal data distribution, these were analyzed running Wilcoxon test and Spearman's rank correlation test.

### *A. Comparing Upper Limb Movements of Subjects Walked at Different Speeds*

The findings in the comparison of the ROM values of HVs at 3 km/h and 5 km/h walking speed values were found significant. The significant difference between the data measured at different speed was found in both cases, the dominant limb ($p<0.01$) and non-dominant limb ($p<0.01$). The median in the dominant limb of the ROMs of HVs performing gait at the speed of 5km/h is 2.3 times larger than the median measured at the speed of 3 km/h. In the measured values of the non-dominant limb, the median of the ROMs of HV who walked at the speed of 5 km/h is 1.8 times larger than the median measured in those walking at the speed of 3 km/h. The comparison of values, in dominant limb ($p<0.01$) and non-dominant limb ($p<0.01$), showed differences in values of AH of HV who walked at 3 km/h and in values during 5 km/h speed. The median of the AHs of HVs walking at the speed 5 km/h is 2.1 times larger than the median of the AHs of HVs who walked at the speed 3 km/h. The median of the AHs of HVs with non-dominant limb walking at the speed of 5 km/h is 1.6 times larger than the median of subjects who walked at the speed of 3 km/h.

TABLE I. HVS' (WALKING AT THE TWO SPEEDS) DOMINANT AND NON-DOMINANT UPPER LIMB COMPARISONS

| | | N-UL | | D-UL | |
|---|---|---|---|---|---|
| | | 3km/h | 5km/h | 3km/h | 5km/h |
| AH | Min ($deg^2$) | $9.26 \cdot 10^1$ | $1.25 \cdot 10^2$ | $1.37 \cdot 10^2$ | $2.75 \cdot 10^2$ |
| | Max ($deg^2$) | $4.55 \cdot 10^2$ | $9.90 \cdot 10^2$ | $5.55 \cdot 10^2$ | $8.65 \cdot 10^2$ |
| | Med ($deg^2$) | $3.16 \cdot 10^2$ | $4.92 \cdot 10^2$ | $2.10 \cdot 10^2$ | $4.46 \cdot 10^2$ |
| | Q1 ($deg^2$) | $1.83 \cdot 10^2$ | $3.22 \cdot 10^2$ | $1.52 \cdot 10^2$ | $3.34 \cdot 10^2$ |
| | Q3 ($deg^2$) | $3.44 \cdot 10^2$ | $6.85 \cdot 10^2$ | $3.33 \cdot 10^2$ | $5.22 \cdot 10^2$ |
| ROM | Min (deg) | 5.7 | 7.7 | 3.5 | 8.6 |
| | Max (deg) | 24.7 | 48.6 | 25.7 | 50.2 |
| | Med (deg) | 13.4 | 23.6 | 10.6 | 24.1 |
| | Q1 (deg) | 9.6 | 18.6 | 8.0 | 17.4 |
| | Q3 (deg) | 16.7 | 31.0 | 15.8 | 26.9 |

AH: area of convex hull; ROM: range of motion; D-UL: dominant upper limb; N-UL: non-dominant upper limb; Mdn: median; Min: minimum; Max: maximum; Q1: first quartile; Q3: third quartile.

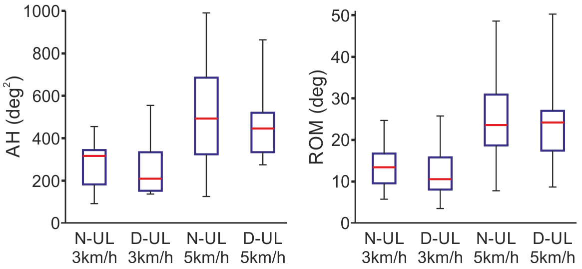

Figure 4. HVs' (walking at the two speeds) dominant and non-dominant upper limb comparisons.

### *B. Comparing Dominant and non-Dominant Upper Limb Movements*

There were no significant differences in the comparison of ROM of dominant and non-dominant limb values. Also, no significant differences were found in both pre-set walking speeds, 3 km/h ($p=0.43$) and 5 km/h ($p=0.95$). The AH values of dominant and non-dominant limbs showed that there are no significant differences in the data in the comparison of pre-set walking speeds, 3 km/h ($p=0.63$) and 5 km/h ($p=0.77$).

### *C. Correlation Between the Area of the Convex Hull and ROM*

The Spearmans rank correlation coefficient indicates, in all cases of the comparison of AH and ROM, moderate to strong correlation. It also shows positive relationship between both quantitative parameters of limb movements. In the first case, the comparison of AH and ROM of the non-dominant limb of HVs walking at the speed of 3 km/h, the measured coefficient indicates a strong correlation ($r=0.76$). In the second case, the comparison of the dominant limb of HVs walking at the speed of 3 km/h, the coefficient showed a moderated correlation ($r=0.54$). The comparison of non-dominant limb of AH and ROM, of HVs walking at the speed of 5 km/h, the measured coefficient indicates a very strong correlation ($r=0.83$). In the comparison of dominant limb of HVs walking at the speed of 5 km/h, the correlation was indicated as moderate correlation ($r=0.47$).

TABLE II. BODY HEIGHT AND QUANTITATIVE PARAMETERS OF UPPER LIMB MOVEMENTS' CORRELATION COEFFICIENTS

| | | N-UL | D-UL |
|---|---|---|---|
| AH | 3 km/h | 0.22 | 0.38 |
| | 5 km/h | 0.12 | 0.36 |
| ROM | 3 km/h | 024 | 0.22 |
| | 5 km/h | 0.01 | 0.17 |

AH: area of convex hull; ROM: range of motion; D-UL: dominant upper limb; N-UL: non-dominant upper limb.

### *D. Correlation bBetween the Body Height and Measured Data*

A weak or negligible correlation was found by all comparisons of AH and body height of HVs performing gait at the speed of 3 km/h and 5 km/h, The same result was found when comparing ROM and body height of HVs walking at the speed of 3 km/h and 5 km/h, see Tab. II.

## IV. DISCUSSION

This work focused on testing and verification of a new method utilizing AH of elbow angle and shoulder angle plots trajectory and found results showing significantly greater AHs of Hvs walking at the speed of 5 km/h if compared to their slower counterparts, reaching almost a twofold value. Despite a rather surprising finding that almost identical results were yielded by ROM, although evaluating only a singe variable (elbow angle), this finding is applicable only to the case of healthy individuals, while it would fail to take abnormalities into account resulting in distorted overall evaluation. On the other hand, the obtained values of AH of HVs do have the potential to evaluate complex upper limb movements among members of a respective age group, indicating the state of a patients upper limb dynamic stability compared to their healthy counterparts. As complex arm movements in relation to each other (dominant versus non-dominant) have not shown relevant differences, the results apply to both arms of an individual universally. The results have also been proven to correspond to those yielded by earlier methods. The study found a range of moderate to very strong Spearmans rank correlation coefficient between AH and ROM ($r>0.45$), universal regardless of measurement variations. This proves the interrelatedness of cyclic patterns of movement in healthy subjects as elbow angle evaluation also relates to shoulder and elbow evaluation. Another observed correlation, the one between body height and the evaluated parameters was revealed to be weak by Spearmans rank correlation test ($r<0.40$) in both speed phases of the experiment which reinforces the universality of AH as it is not influenced by the subjects height. The analysis also rejected the requirement of data normalization since under uniform conditions (strict measurement unit location for all subjects) all adult subjects angle ranges were identical. The method presented in this work pointed out to the capability of AH to clarify mechanisms in balance during gait, relying on the evaluation of the course of two most important joint angles, enabling it to evaluate complex limb movement as a whole, as opposed to other methods such as local dynamic stability [32], [33]. Therefore, we are talking rather about a quantification of global stability. As for dynamic stability quantification, it is described by the area of convex hull, the larger the area (i.e. trajectories differing on a larger scale, as well as in their shapes), the less dynamically stable the system. The comparison of the new technique with more traditional methods also posed possible limitations. The major one perhaps being the actual size of the subject sample, since a number of ten HVs may not present a solid base for absolute conclusions. Despite finding statistically relevant results, their verification in a wider research paper are still a possibility. Still, as seen in similar works, a sample size counting ten subjects meets the requirements of testing basic attributes of the examined parameter [34]. Since traditional methodology relying on a single dimension evaluation fails to focus on complex arm movements together with balance and posture control during gait in the field of medical practice, the presented method should be perceived as a possible research tool for the field.

## V. CONCLUSIONS

The paper proved that the method of convex hull, i.e. the area of the angle-angle diagram as a basis for research into dynamic stabilty and upper limb movement patterns during gait represents a suitable tool for the assessment and revealing of balance and posture changes and inevitable upper limb coordination during walking. The proposed method provides for distinction of various levels of dynamic instability with respective walking specifications, and the results are partially in accordance with those yielded by more common methods (e.g ROM). Still, more traditional methods fail to evaluate complex arm movement in its entirety as they ignore mutual evaluation of the two main joint angles. It appears that the method, relying on the data from a set of inexpensive gyroscopes proves as a tool for quantification of dynamic stability during gait, making it a part of clinical and biomechanical examinations. The proposed methods design may also find its way to physiotherapists and physicians as a means of diagnostic tool for illnesses and tiredness, as well as find its use in MoCap systems software or driven prostheses to process movement patterns. The future works objective will be the methods use in disabled patients and quantification of dynamic instability over the period of recovery.

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