Trajectory Analysis in the Aikido Technique Shiho Nage

Adina L. CIOBANU and Dana M. VÎLCU

Abstract—**Aikido is a modern Japanese martial art. The basic principle of its techniques is to avoid the attack and to direct its energy on a curve around the defender. Those curves are considered spherical in some intuitive sense, and are described as such in some Aikido literature. This paper presents a first formal evidence that trajectories described during the performance of the Aikido technique Shiho Nage actually are approximations of spherical spirals. The software tools and the basic mathematical model employed in our research are presented.**

Index Terms—**trajectory analysis, spherical spiral, Aikido technique, R language.**

I. Introduction

Trajectory analysis of various movements is useful both in sports and in medical recovery physical exercises, with the natural purpose of performance improvement. Of course, the analysis assumes a comparison of the recorded movements with some ideal model or with previous recordings. See for example [1, 2]. Our paper brings a contribution to this topic. More precisely, we analyze trajectories generated by an Aikido technique called Shiho Nage, aiming to identify a mathematical model for them.

In Aikido dojos, and in some Aikido literature, it is talked about the spiral [3] or spherical [4] form of movements in Aikido techniques, though (only) at an intuitive level. Formalizing those statements was our original motivation.

Our starting point was a digital recording of the Shiho Nage technique performed by an Aikido expert, described in the next section. The software tools we employed and developed are described in Section III. In Section IV we present the preliminary data processing, while in Section V we present the study of the respective movement. Section VI is devoted to spherical spirals and their approximations. It allows us to conclude, in Section VII, that the trajectory of the front hand approximates the mathematically theoretical curve of a loxodrome. Perspectives and future work are also given in Section VII. To ease the reading, a very few Japanese terms are introduced in Apendix A.

II. Data Recording

The recording of the movements of Nage (the person performing the technique) was done with the Xsens MVN™ system. It is based on inertial sensors worn by Nage. The sensor information is sent wireless to a system (MVN Fusion Engine) which contains data fusion algorithms based on biomechanical models. The whole set is completed by MVN Studio, software in which you get the visualization of the movement through an avatar (see Fig. 1). The result of aggregating the information from the sensors is stored in MVNX files. They contain information on the position, speed, linear and angular acceleration and much more, about 23 body segments. All kinematic data are expressed in a global coordinate system.

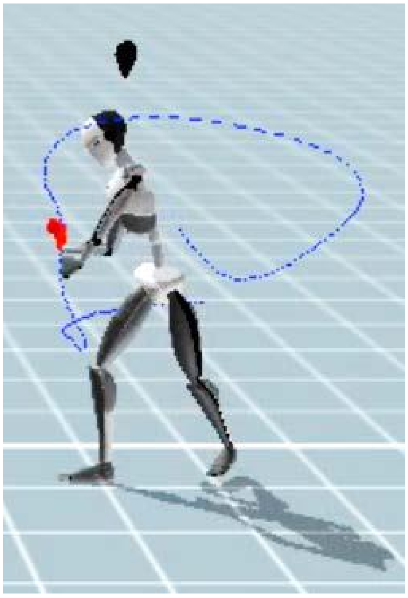

Figure 1. MVN Studio conversion of the motion based on the sensors. One coordinate axis (white) partially included

III. Technologies Used for the Development of Our Analysis Tools

The data processing, analysis and visualization was done using the R language and its various packages:

- ggplot2 (2D graphics, different point layers, coordinate systems, scaling),
- plot3D (3D graphics, figures, surfaces, volume view, etc.),
- rgl (for interactive figures obtained with OpenGL or WebGL),
- XML (for reading XML files, extracting root node and elements, transforming input into data frame),
- Shiny (for developing a web application in R by integrating with R Markdown),
- Tidyvers (for creating an application by loading all packages into one command),
- R Markdown (creating web pages),

A. L. CIOBANU was undergraduate student at Military Technical Academy "Ferdinand I" when she developed the software tools used in this paper. She is now a graduate student at "Politehnica" University of Bucharest, Faculty of Automatic Control and Computer Science (e-mail: adina_luiza.ciobanu@stud.acs.upb.ro).

D. M. VÎLCU is scientific researcher of Military Technical Academy "Ferdinand I", Bucharest, Romania (e-mail: dana.vilcu@mta.ro).

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- NISTunits (file analysis, for processing related to measurement units),
- LearnGeom (geometry calculations),
- Sphereplot (display of points on the sphere, reciprocal transformation of Cartesian and spherical coordinates).

IV. Preliminary Processing

We chose for our analysis the Shiho Nage technique, which is learned by the beginners and therefore practiced a lot. It was performed against an Yokomen Uchi attack.

We considered the trajectory described by the front hand of Nage (precisely, by its palm wrist), the one which takes over the attacker's energy. To properly identify the respective data, preliminary processing of the files was necessary.

First of all, the data of interest must be extracted from the mvnx file.

One first way to extract useful data was by:

- parsing the mvnx file (done using a script written in the php language),
- selecting the position points in the frames, inserting them into a file, separated by a comma, and
- adding the table header corresponding to all the points considered and the three coordinates of each.

This results in a csv file.

Another parsing method was done in R language. Using the XML package, the content of the file was retrieved as a list. One extracts and concatenates the names of the segments (in the "segments" column), the axes of each, followed by the corresponding positions, for each moment of time. Based on them, a data frame is created with the position of each segment during the entire recording. The result is a csv file.

Displaying the sequence of coordinates for each point allows us to view the movement of that point. Thus, Fig. 2 shows the 2D motion view, and the z-axis is transposed in color. The representation of the same motion is transposed in 3D in Fig. 3.

Figure 2. 2D representation of motion, based on raw data

For further analysis it is necessary to know the duration between recording two consecutive points, obtained as the ratio between the duration of the entire recording and the total number of points. The duration of the entire recording is determined, in milliseconds, by the difference in the time value from the first and the last <frames> tag. The total number of records is given by the number of data lines of the .csv file obtained previously.

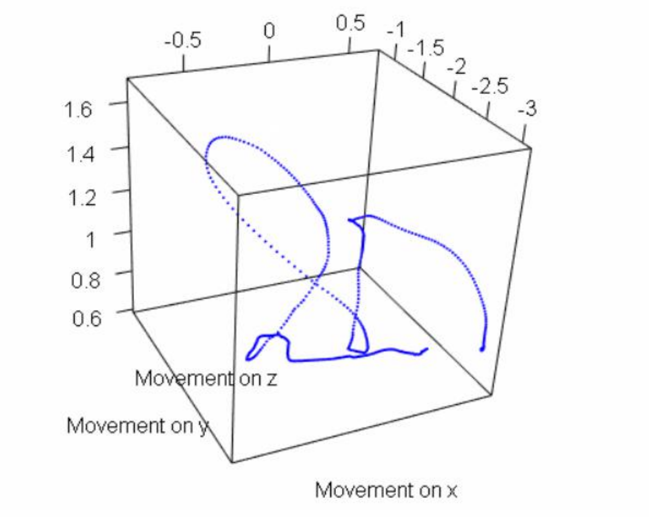

Figure 3. 3D representation of motion, based on raw data

Once the palm movement data has been extracted, the residual data must be removed from the data of interest. Namely, the recording begins before the actual start of the technique and ends after its conclusion. The identification of these beginning and end fragments is based on a principle of Aikido techniques, thus being independent of the making of the recordings. Precisely, the curve of interest begins when all the points move, which means, in fact, the movement of the center of mass *m*. And that curve ends the moment *m* remains in equilibrium. Due to the high frequency with which the data are recorded and their accuracy (six digits after the decimal point), it was agreed that it would be sufficient to estimate the start and end of the movement when changes occur at the level of the third digit after the comma.

Corresponding to the start and end moments of the curve, the start and the end points of the curve to be analyzed are determined, thus allowing the comparative analysis of the movement within the mp4 file.

The reduced curve according to the previous principles and whose shape will be analyzed is shown in Fig. 4.

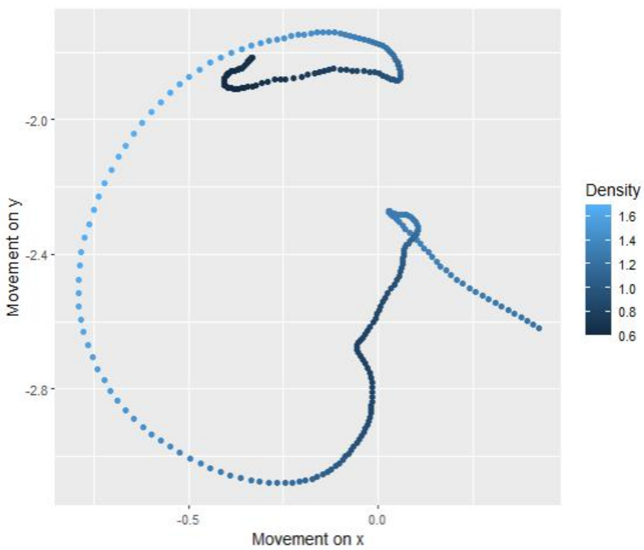

Figure 4. Front palm's trajectory in the execution of Shiho Nage

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V. Study of the Curve Form

Studying the shape of the curve trajectory involves several stages.

Step 1: The movement of the palm with respect to the shoulder

Due to the characteristics of the analyzed technique and due to the correctness of its execution, it can be considered (i.e., approximated) that, relative to the shoulder, the palm moves on a sphere.

Thus, if *P* is the point that represents the palm, and *U* the shoulder of the same hand, in the initial coordinate system, we have:

$$\vec{S} = \vec{P} - \vec{U}, \tag{1}$$

$$\|\vec{S}\| = \|\vec{P} - \vec{U}\|, \tag{2}$$

$$\|\vec{S}\|^2 = (x_P - x_U)^2 + (y_P - y_U)^2 + (z_P - z_U)^2. \tag{3}$$

Our software measurements confirmed that $\|\vec{S}\|$ is almost constant, showing that, for most time of the technique's performance, the hand was slightly flexed, but not bent.

The coordinates of the palm with respect to the shoulder are given by:

$$S\,(x_P - x_U,\quad y_P - y_U,\quad z_P - z_U). \tag{4}$$

The representation of this motion on the sphere of center *U* and radius $\|\vec{S}\|$ is given in Fig. 5.

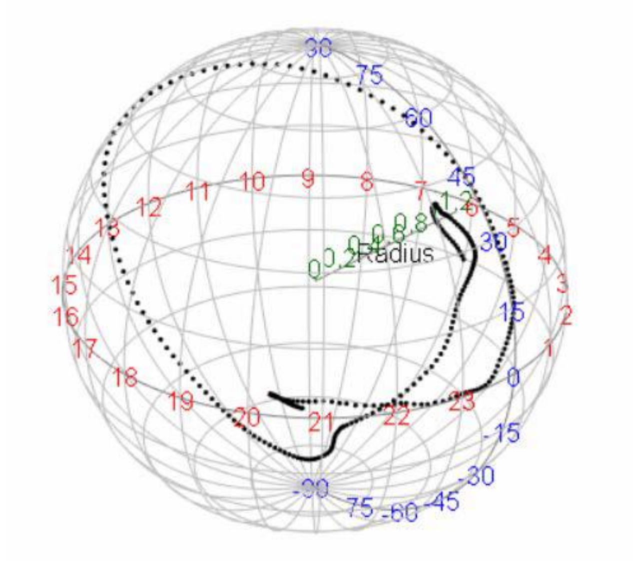

Figure 5. The movement of the palm with respect to the shoulder

Step 2: The decomposition of the motion

The execution of the technique involves two important phases: the first one is taking over the attack, and the second one is driving the energy towards the technique's completion (see [4] for details). Our working assumption is that those phases correspond to two distinct curves on the sphere, separated by an inflection zone, which is itself a certain curve.

The curve corresponding to the analyzed motion is approximated by the coordinates of the points taken at equal times. We consider the curve formed by vectors of the length of each segment determined by two consecutive points. The vertex of each such vector is the origin of the next vector. For each point of the motion, we call *turning angle* the angle made by the two adjacent vectors that have an extremity at that point.

We call *inflection point* the point at which the direction of the curve of motion with respect to the associated vector changes significantly. Let $\vec{u}$ and $\vec{v}$ be the vectors given by the two segments adjacent to a point *p*, the first with the vertex at *p* and the other with the origin at *p*, and each having the same length as the respective segments. We have:

$$\langle \vec{u}, \vec{v} \rangle = \|\vec{u}\| \|\vec{v}\| \cos\left(\|\widehat{\vec{u}, \vec{v}}\|\right), \tag{5}$$

$$\langle \vec{u}, \vec{v} \rangle = x_u x_v + y_u y_v + z_u z_v. \tag{6}$$

Therefore we get:

$$\cos\left(\|\widehat{\vec{u}, \vec{v}}\|\right) = \frac{x_u x_v + y_u y_v + z_u z_v}{\|\vec{u}\| \|\vec{v}\|} \tag{7}$$

$$\cos\left(\|\widehat{\vec{u}, \vec{v}}\|\right) = \frac{x_u x_v + y_u y_v + z_u z_v}{\sqrt{x_u^2 + y_u^2 + z_u^2}\sqrt{x_v^2 + y_v^2 + z_v^2}}, \tag{8}$$

where

$$x_u = x_2 - x_1,\ y_u = y_2 - y_1,\ z_u = z_2 - z_1 \tag{9}$$

$$x_v = x_3 - x_2,\ y_v = y_3 - y_2,\ z_v = z_3 - z_2 \tag{10}$$

The time variation of $\|\vec{u}\|$ can be found in Fig. 6.

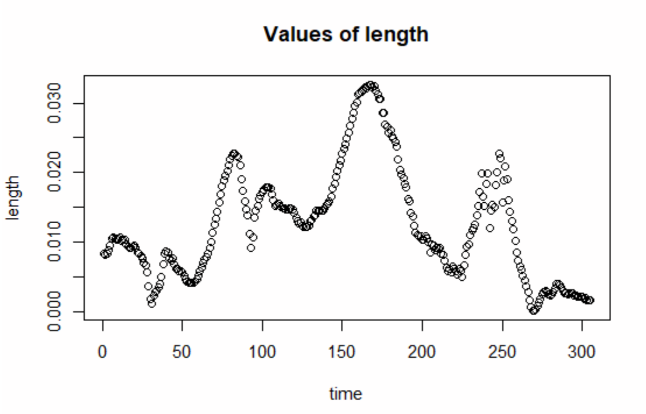

Figure 6. The distances between consecutive points

The cosine values are represented in Fig. 7.

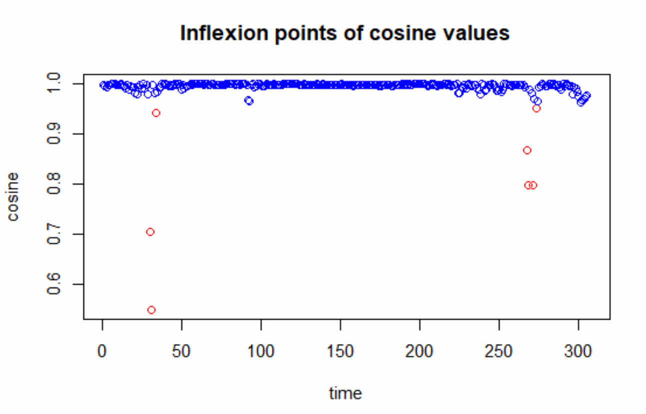

Figure 7. The value of the cosines of the turn angles

The resulting turn angle values are given in Fig. 8.

The number of occurrences of a certain angle (measured in degree), normalized to the unit interval, can be found in Fig. 9.

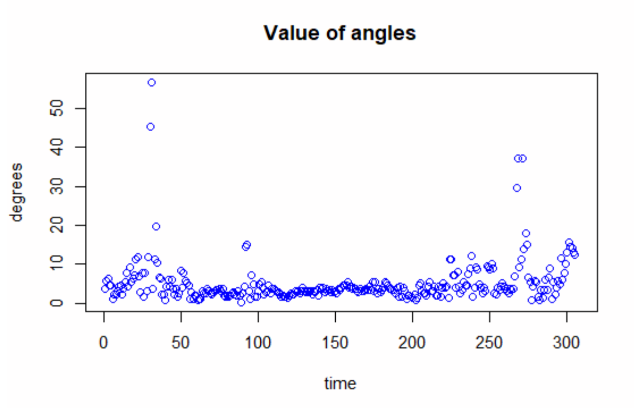

Figure 8. The turn angles

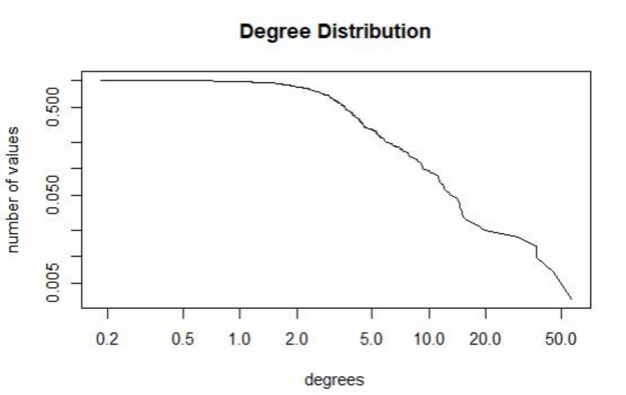

Figure 9. Normalized occurrences of an angle value

The transition from taking over the attack to directing the movement on a certain trajectory determines an inflection zone, in which the value of the cosine of the turn angles varies. For the analyzed motion we observe (Figs. 7-8) that, in the interval given by the positions 35 and 266, the value of the cosine is approximately constant. The movement corresponding to this interval is presented in Fig. 10.

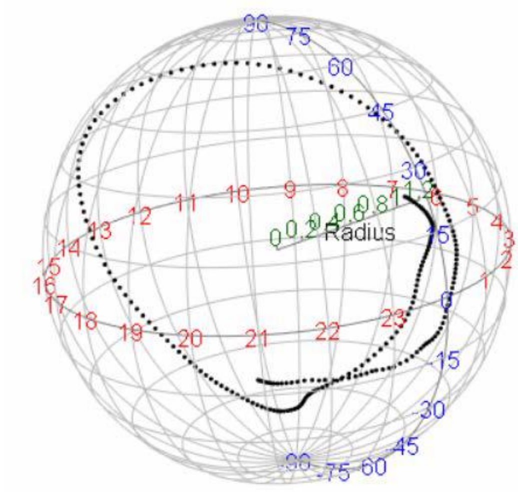

Figure 10. Sphere representation of the motion for the interval of almost constant cosine of turn angles

VI. Spiral Approximation

As mentioned before, an Aikido technique can be decomposed into three phases, each of which could be a spiral.

Formally, a *spherical spiral* is the curve described by a point moving from the North Pole to the South Pole of a sphere while keeping a constant (but not right) angle with the meridians. (see Fig. 11, reproduced from [5]. The corresponding webpage allows modifications of the drawing, according to the spiral parameters.) It is also known as a *rhumb line*, or a *loxodrome*. More details can be found in [6].

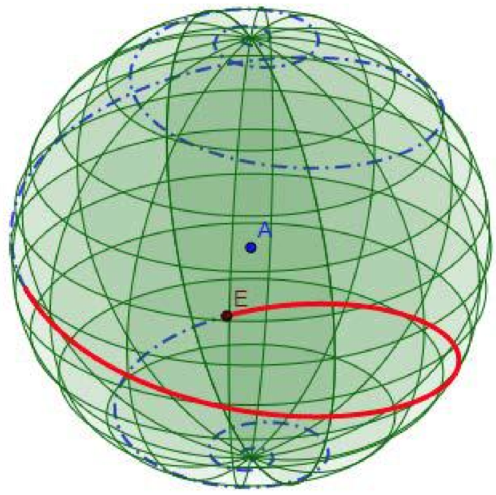

Figure 11. A spherical spiral, as drawn in [5]

For our considerations, we took another two steps.

Step 3. Consider the original position of the palm as the North Pole of the sphere

This can be achieved by a change of coordinates composed by two rotations, as described next.

Let $P_0 = (x_0, \ y_0, \ z_0)$ be the starting point of the movement. The first rotation, of angle θ, maps P_0 to $P_0' = (x' = 0, \ \ y', \ \ z' = z_0)$ so

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} \tag{11}$$

$$\begin{cases} x' = x_0 \cos\theta - y_0 \sin\theta = 0 \\ y' = x_0 \sin\theta + y_0 \cos\theta = \sqrt{x_0^2 + y_0^2} \end{cases} \tag{12}$$

Hence

$$\tan\theta = \frac{x_0}{y_0}, \tag{13}$$

$$\theta = \tan^{-1} = \frac{x_0}{y_0}. \tag{14}$$

The second rotation maps $P_0' = (0, \ \ y', \ \ z_0)$ to $P_0'' = (0,0,1)$, and its rotation angle φ is given by

$$\varphi = \tan^{-1} = \frac{y'}{z_0}. \tag{15}$$

The above composition of two rotations is applied to all points which describe the movement of the palm with respect to the shoulder.

Step 4. Compare the trajectory with a spherical spiral

With t the arc-parameter, the coordinates of a point $p(x, y, z)$ on a spherical spiral are given by

$$x = \frac{\cos t}{\sqrt{1+a^2t^2}}, y = \frac{\sin t}{\sqrt{1+a^2t^2}}, z = \frac{-at}{\sqrt{1+a^2t^2}}, \tag{16}$$

where a is a constant [5].

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One easily gets from the above that

$$t = \tan^{-1}\frac{y}{x}, \tag{17}$$

and therefore

$$a = \frac{z}{\sqrt{1-z^2}}\frac{1}{\tan^{-1}\frac{y}{x}}. \tag{18}$$

For each point obtained via the coordinate transform previously described, we compute the parameter a with the above formula. If its value is almost constant, we consider that the respective arc of curve approximates a spherical spiral.

The actual values we obtained are represented in Fig. 12.

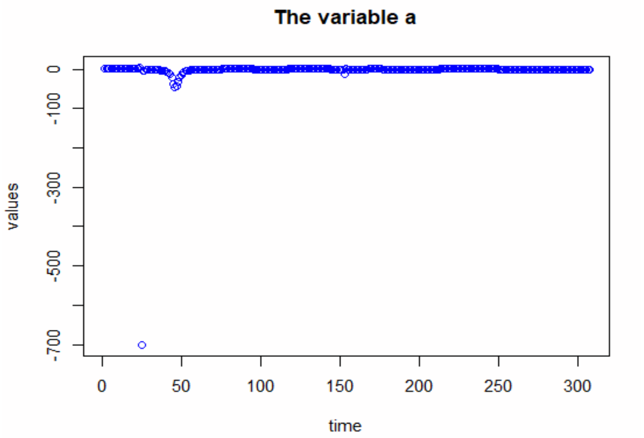

Figure 12. The variation of the parameter *a*

One can remark the existence of two time intervals for which a is almost constant, determining two spirals. Compare Fig. 10 to Fig. 11.

Watching the video recording for the respective time intervals, we noticed that the two loxodromes indeed correspond to the first and the last phase of the technique.

In some intuitive sense, the first spiral is contractive, while the second one is expansive.

VII. Conclusion

In this article we bring a formal evidence that the trajectory of the palm of the front hand of Nage, performing the Shiho Nage technique in Aikido, is a spherical spiral relative to the shoulder. Prior work includes movement analysis in other martial arts, and intuitive description of spiral and round movements in Aikido [7, 8].

Even though the above conclusion may seem somehow spectacular, we emphasize that the identified spherical spirals are actually small arcs, in the sense that they are involving less than 2π rotation angle.

This study is a first step towards, and it is foundamenting, a more general goal. The methodology we developed can be used to analyze trajectories corresponding to other techniques, either in Aikido or in other martial arts. We leave this for future investigation [10].

We also leave for future work finding a bio-mechanical explanation, based on the Aikido principles, of why the respective trajectories are spherical spirals [10].

It is common wisdom in martial arts that the movements of the human body should all start from its mass center m. Therefore, it could be of definite interest to consider the palm trajectory with respect to m, too.

At a practical level, our approach could also be useful during the process of technique learning and improvement, through a better understanding of the master level performance trajectories, and by comparisons of the trajectories of high level students with those of great masters.

Appendix A – Terminology

Here we briefly present a very few Japanese terms, aiming to ease the reading of this paper [9].

Aikido (“way of harmonizing energy”) – a Japanese martial art that uses twisting and throwing techniques, and pressure on vital nerve centres, in its aim of turning an attacker’s strength and momentum against himself [4].

Dojo – a hall where a martial art is practiced.

Nage – the person which performs the Aikido technique. The word also means throw.

Shiho Nage – an Aikido technique also known as *the four direction throw*, or *the four corner throw*.

Yokomen Uchi – a circular horizontal strike to the head.

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This work is part of a larger project, involving a larger team [10]. Costin Boldor (3 Dan Aikido, *Romanian Aikido Federation*) performed the Aikido techniques and provided the video recording. Andrei Dragomir, Scientific Researcher III at *National Research Institute for Sports*, helped us with recording the data by use of the Xsens MVN™ system, and offered valuable hints on how to use the resulting files. Costin Vîlcu, Scientific Researcher I at *Simion Stoilow Institute of Mathematics of the Romanian Academy*, initiated the study of trajectories of Aikido techniques and provided insights into those techniques. We deeply thank them all for the opportunity to work on this topic.

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