PLAViMoP: How to standardize and simplify the use of point-light displays

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Abstract

The study of biological point-light displays (PLDs) has fascinated researchers for more than 40 years. However, the mechanisms underlying PLD perception remain unclear, partly due to difficulties in precisely controlling and transforming the PLD sequences. Furthermore, little agreement exists for each transformation. This paper introduces a new free-access program called PLAViMoP (Point-light Display Visualization and Modification Platform) and presents the algorithms used for PLD transformations actually included. PLAViMoP fulfills two objectives. First, PLAViMoP standardizes and makes clear many classical spatial and kinematic transformations described in the PLD literature. Furthermore, given its optimized interface, PLAViMOP makes the achievement of these transformations easy and fast. Overall, PLAViMoP could directly help scientists avoid technical difficulties and focus directly on data analysis and interpretation and could make possible the use of PLDs for non-academic applications.

Background and Motivation

More than forty years ago, it was shown that human beings are highly sensitive to biological motion produced by living organisms. In a seminal paradigm, Johansson, a Swedish researcher, demonstrated that this sensitivity for biological motions was mainly related to the capacity to interpret kinematics. From minimalist motion sequences that contained only small lights representing an actor's major joints, he demonstrated that people are able to recognize numerous actions such as walking or dancing (Johansson, 1973): the method of point-light display (PLD) was born. Since this first study, many researchers and non-researchers have seized upon this technique to better understand the mechanisms underlying visual perception of biological movements or, in a more applied framework, to improve sports performance, rehabilitation techniques or even the technologies used in the film and video game industries. In this perspective, many studies have been performed to improve the capture, the visualization and the modification of PLDs. However, to date, there are still many questions related in particular to the absence of clear algorithms concerning the different transformations of point-light sequences. In this paper, we introduce new software called PLAViMoP (Point-light Display Visualization and Modification Platform[1]) with the objective of standardizing and facilitating the visualization and modification of PLDs. After a brief review of the PLD literature, our paper details the algorithms and functions included in our new software, PLAViMoP. The last part of the paper is devoted to a discussion about possible uses of our tool for scientific experts as well as from more applied perspectives.

Since the first study by Johansson (1973), PLDs have been enthusiastically adopted by scientists, and many studies have been conducted using this method (for reviews, see Bidet-Ildei, Orliaguet, & Coello, 2011; Blake & Shiffrar, 2007; Pavlova, 2012). Globally, these

[1] PLAViMoP is registered to the « Agence pour la Protection des Programmes since May 2017 (Inter Deposit Digital number: IDDN.FR.001.200011.000.S.P.2017.000.31235)

studies have confirmed that humans have very high sensitivity to this type of animation. In fact, humans can recognize many of the biological actions of living organisms from PLDs (e.g., Johansson, 1973; Pavlova, Krageloh-Mann, Sokolov, & Birbaumer, 2001), as well as the gender (Kozlowski & Cutting, 1977; Pollick, Kay, Heim, & Stringer, 2005; Troje, Sadr, Geyer, & Nakayama, 2006), identity (Beardsworth & Buckner, 1981; Loula, Prasad, Harber, & Shiffrar, 2005; Troje, Westhoff, & Lavrov, 2005), emotion (Atkinson, Dittrich, Gemmell, & Young, 2004; Chouchourelou, Matsuka, Harber, & Shiffrar, 2006; Clarke, Bradshaw, Field, Hampson, & Rose, 2005; Dittrich, Troscianko, Lea, & Morgan, 1996), intention (Chaminade, Meary, Orliaguet, & Decety, 2001; Davila, Schouten, & Verfaillie, 2014; Iacoboni et al., 2005; Louis-Dam, Orliaguet, & Coello, 1999; Martel, Bidet-Ildei, & Coello, 2011) and personality traits (Thoresen, Vuong, & Atkinson, 2012) of the observed human stimuli. Moreover, properties of manipulated objects, such as weight (Runeson & Frykholm, 1981) or size (Jokisch & Troje, 2003), can also be detected via PLDs.

Interestingly, the capacities required for perceiving PLDs appear at birth (Bardi, Regolin, & Simion, 2011; Bidet-Ildei, Kitromilides, Orliaguet, Pavlova, & Gentaz, 2014; Simion, Regolin, & Bulf, 2008) and were related to the activation of specific parts of the brain (see Giese & Poggio, 2003; Pavlova, 2012 for reviews), including those involved in motor skills (e.g., Bonda, Petrides, Ostry, & Evans, 1996; Grézès et al., 2001; Grossman et al., 2000; Saygin, Wilson, Hagler, Bates, & Sereno, 2004; Sokolov, Gharabaghi, Tatagiba, & Pavlova, 2010; Vaina, Solomon, Chowdhury, Sinha, & Belliveau, 2001; van Kemenade, Muggleton, Walsh, & Saygin, 2012). The involvement of motor system during PLD processing was also confirmed by developmental (Louis-Dam et al., 1999) and neuropsychological studies (Chary et al., 2004; Pavlova, Bidet-Ildei, Sokolov, Braun, & Krageloh-Mann, 2009) which shown a positive link between motor performance and the ability to recognize PLD.

Finally, in addition to the interest in understanding the mechanisms involved in the visual perception of biological movements, other authors have been interested in the links between this perceptual capacity and other cognitive or social abilities. In this context, it has been shown that the visual perception of human movements is closely related to the abilities underlying social cognition, concerning the recognition of emotions, the interpretation of others' behavior or even the level of empathy (see Pavlova, 2012 for a review). In the same manner, the sensitivity to biological motion is related to higher cognitive functions such as the processing of language and numbers. Indeed, it has recently been shown that listening to or reading an action verb increases the capacity to recognize a congruent point-light action embedded in masking dots (Bidet-Ildei, Gimenes, Toussaint, Almecija, & Badets, 2016; Bidet-Ildei, Sparrow, & Coello, 2011). In the same vein, the observation of a pointing movement directly affects the capacity of humans to generate numbers. In relation to the mental number line concept, in which small quantities are represented on the left side and large quantities on the right side (Dehaene, 1992), it has been shown that the observation of a pointing movement directed toward the left side increases the probability of generating a small number, whereas the observation of a pointing movement directed toward the right side increases the probability of generating a large number (Badets, Bidet-Ildei, & Pesenti, 2015).

Altogether, this brief review underlines the role of PLDs in our understanding of the reciprocal links between action, perception, and cognition.

One important issue in the PLD literature is the need to better specify the mechanisms behind PLD processing and the factors that modulate PLD processing. To date, several questions remain under debate, such as the roles of local and global information (e.g., Bardi et al., 2011; Chang & Troje, 2009), the impact of motor and visual experience (see Bidet-Ildei, Orliaguet, et al., 2011 for a review) and the role of sex differences in perceptual performances (e.g., Pavlova, Sokolov, & Bidet-Ildei, 2015). Moreover, whereas links have been demonstrated between the processing of biological motion and the processing of language (Beauprez & Bidet-Ildei, 2017; Bidet-Ildei, Gimenes, Toussaint, Beauprez, & Badets, 2017a; Bidet-Ildei, Sparrow, et al., 2011; Bidet-Ildei & Toussaint, 2015; Pavlova et al., 2015), numbers (Badets et al., 2015) or social activities (Atkinson et al., 2004), the specificity of these links and their neural substrates remain open questions.

To disentangle these issues, a valuable methodology consists of modifying natural PLDs and assessing the consequences of these modifications on perceptual capacities. Using this methodology, several studies have investigated the consequences of spatial and/or temporal modifications of biological PLDs on perceptual competencies (see Appendix 1 for a list of references using PLD transformations). Spatial perturbations can simply consist of showing the PLD using an unnatural orientation (e.g., Pavlova & Sokolov, 2000; Simion et al., 2008; Sumi, 1984; Verfaillie, 2000), playing it backwards (e.g., Klin, Lin, Gorrindo, Ramsay, & Jones, 2009) or with shifting dots along the articulated limbs (e.g., Beintema & Lappe, 2002). Spatial transformations can also consist to average some PLDs with spatio-temporal morphing (e.g., Jastorff, Kourtzi, & Giese, 2006; Thoresen et al., 2012; Troje, 2002). Finally, it is possible to disturb the spatial coherence of the animation by scrambling the positions of the joints ("scrambled motions"; e.g., Bidet-Ildei et al., 2014; Grossman et al., 2000; Hirai & Hiraki, 2005; Hiris, 2007; Simion et al., 2008), by using temporal or spatial bubbles (Thurman & Grossman, 2008) or by using pair-wise motions which preserves the local pendular movements associated with individual limbs (Jejoong Kim, Jung, Lee, & Blake, 2015). Overall, these different studies have shown that the capacity of humans to perceive and recognize biological motions is closely related to the spatial properties of the movement, such as a canonical orientation (Pavlova & Sokolov, 2000) and the spatial coherence of the movement (Grossman et al., 2000; Hirai, Senju, Fukushima, & Hiraki, 2005). Moreover, changing the orientation of PLD may lead to a bias in the sense that observers often perceive a PLD as facing toward them

(Vanrie, Dekeyser, & Verfaillie, 2004). Interestingly, the sensitivity to the spatial specificities of PLD is present at birth. In fact, the gaze of newborns aged 2-4 days was oriented more toward a canonical biological PLD than toward an upside-down equivalent and more toward biological than scrambled PLDs (Simion et al., 2008).

Other modifications consist of modifying the kinematics of each dot constituting the PLD while maintaining the spatial trajectory and total duration of each dot. Previous studies have rendered the biological movement non-biological by modifying the velocity along the path using a constant velocity, a linear acceleration, or an inverse velocity (Bidet-Ildei, Kitromilides-Salerio, Orliaguet, & Badets, 2011; Bidet-Ildei, Meary, & Orliaguet, 2008; Bidet-Ildei, Orliaguet, Sokolov, & Pavlova, 2006; Bouquet, Gaurier, Shipley, Toussaint, & Blandin, 2007; Martel et al., 2011; Pozzo, Papaxanthis, Petit, Schweighofer, & Stucchi, 2006). When PLD violated the biological kinematic laws, recognition was generally degraded (Bouquet et al., 2007). Moreover, non-biological velocity drastically reduced the capacity to anticipate the final position of a human movement presented as a PLD (Martel et al., 2011; Pozzo et al., 2006) and could affect the natural link between number and space (Badets et al., 2015).

Finally, one another way to study PLDs consists of camouflaging the PLD with dynamic masks (Cutting, Moore, & Morrison, 1988), which consist of several dots placed at random positions. Each dot of the mask can move with different dynamics corresponding to linear, random or scrambled motions (Bidet-Ildei, Chauvin, & Coello, 2010; Cutting et al., 1988; Hiris, 2007). However, the duration of presentation (Cutting et al., 1988; Thornton, Pinto, & Shiffrar, 1998), the type of mask (Cutting et al., 1988; Hiris, 2007) and the number of masking dots (Bidet-Ildei et al., 2010; Cutting et al., 1988; Hiris, 2007) directly influence the perception of biological motion. When the duration of the target-stimulus presentation is close to 200 ms, different types of dynamic masks (i.e., linear, random, and scrambled motion) can dramatically impede the ability to recognize human point-light display. In contrast, when the duration of the target stimulus is longer than 400 ms, only the masks composed of scrambled dynamic components of the target stimulus can significantly decrease perceptual performance, whereas the masks composed of random or linear motions do not influence participants' sensitivity (Cutting et al., 1988; Hiris, 2007) compared to PLDs without masks.

Altogether, these studies show that perturbing spatial-temporal PLD characteristics is a valuable methodology to better understand the mechanisms behind the considerable capacity of humans to perceive and interpret biological movements. However, despite the number of studies that have used spatial and kinematics transformation of PLD, there is no clear description of algorithms used to make these transformations. This lack of transparency can affect the reproducibility of results and can even generate ambiguities. For example, in the literature, there is ambiguity regarding the scrambled label, which is used both by people who have randomized the initial spatial position of each dot constituting their original PLD in a specific window (e.g., Bidet-Ildei et al., 2014) and by people who have randomly permuted the positions of the different dots constituting the original PLD (e.g., Nackaerts et al., 2012a). Moreover, studies rarely detail whether changes in kinematics were made on each component of the velocity or directly on the norm of the velocity. Yet, these two types of transformation can lead to completely different configurations. In the same way, when a z-axis spatial rotation is executed, it is not always specified from which point of origin the rotation is performed, with most studies simply using the terms "inverted" or "upside down". The second difficulty in applying PLD transformations is the number of steps and calculations required to execute them. For example, the inversion of the velocity norm necessitates 1) recovering the coordinates of the biological movement (here, it is possible to directly capture the motion or to keep the coordinates in an existing database, see for example the base of Shipley & Brumberg (2004), 2) calculating the tangential velocity and the trajectory evolution along the path, 3) calculating the mean of the velocity, 4) modifying the biological tangential velocity to have acceleration when biological motion decelerate and deceleration when biological motion accelerate, 5) retrieving new coordinates of motion that respect the new tangential profile and keep the spatial trajectory of the movement 6) generating the new stimulus. Performing all these steps takes time, increases the risk of error, and limits the use of PLDs to an academic environment when several applications could be imagined.

Even if some tools have tried to facilitate the modification of PLDs as the bio-motion toolbox of Matlab (van Boxtel & Lu, 2013), to our knowledge, it does not exist a simple software which allows the transformation of PLDs without programming competencies (but see the online demonstration of Niko and Troje https://www.biomotionlab.ca/Demos/BMLwalker.html). In this article, we introduce PLAViMoP software[2] (Point-light Display Visualization and Modification Platform), a new free access program that allows both the transformation and visualization of PLDs. The first objective of PLAViMoP is to standardize the spatial, temporal and dynamic transformation classically applied to PLDs (see Appendix 1 for a review of the transformations used in the literature that can be performed with PLAViMoP). The second objective of PLAViMoP is to make all these transformations easy and fast. By allowing the automatic realization of all steps in a standardized routine, PLAViMoP will facilitate the applications of PLD transformations by scientists and will allow non-specialists with limited access to technological resources to use biological movement transformations in line with their specified needs (motor reeducation, sports training, etc.). The third objective is to allow spatial and kinematic transformations both in 2D and 3D spaces; this offers the possibility of easily generating the PLD from various points of view (perspectives) rather than only a side or front view. Even if we are aware that 3D PLDs are ambiguous relative to 2D displays (e.g., Rehg, Morris, & Kanade, 2003), the Mokka part of PLAViMoP proposes various tools (e.g., adding a grid floor, coloration of points to differentiate right and left sides, creation of links between

[2] PLAViMoP software is one component of PLAViMoP platform. The second component is PLAViMoP Database a new Database in free access with several point-light motions representing human movements.

points to model a skeleton, simultaneously proposing two different angles of view) to remove this ambiguity (See Figure 1 for one example). Finally, PLAViMoP allows managing several point-lights together in order to facilitate the study of social interactions. In addition, it can run from sophisticated capture systems (e.g., Vicon or Qualisys) but also from very simple systems (e.g., leap motion) and even from point-light created by computer simulation (Cutting, 1978) since a plug-in ("CSV2C3D" provides with PLAViMoP software) allows to create a c3d file from an Excel file that specifies the set of coordinates (X, Y, Z) as a function of time.

In the next section, a description of PLAViMoP and its transformations is presented, along with potential applications. We decide to include in our program, a lot of functionalities that are classically used in literature (see Appendix 1 for a list of various papers that have used many different tools as references to apply transformations) even we are conscious that we are not exhaustive. The idea is first to standardize the modifications that have already been applied in some research papers. However, PLAViMoP is a collaborative platform and therefore new transformations and new functionalities could be added through plug-in. Thanks to standardized transformations, its ease of use and its collaborative approach, we hope that PLAViMoP will be used and developed by the researchers' community[3].

Implementation and Examples

PLAViMoP is composed of a MATLAB graphical user interface interacting with the free, open-source program Mokka (Barre & Armand, 2014). Figure 1 presents a global view of the software.

[3] New functionalities should be programmed in Matlab. Only users who have the status of contributor can propose new functionalities to enrich PLAViMoP Software.

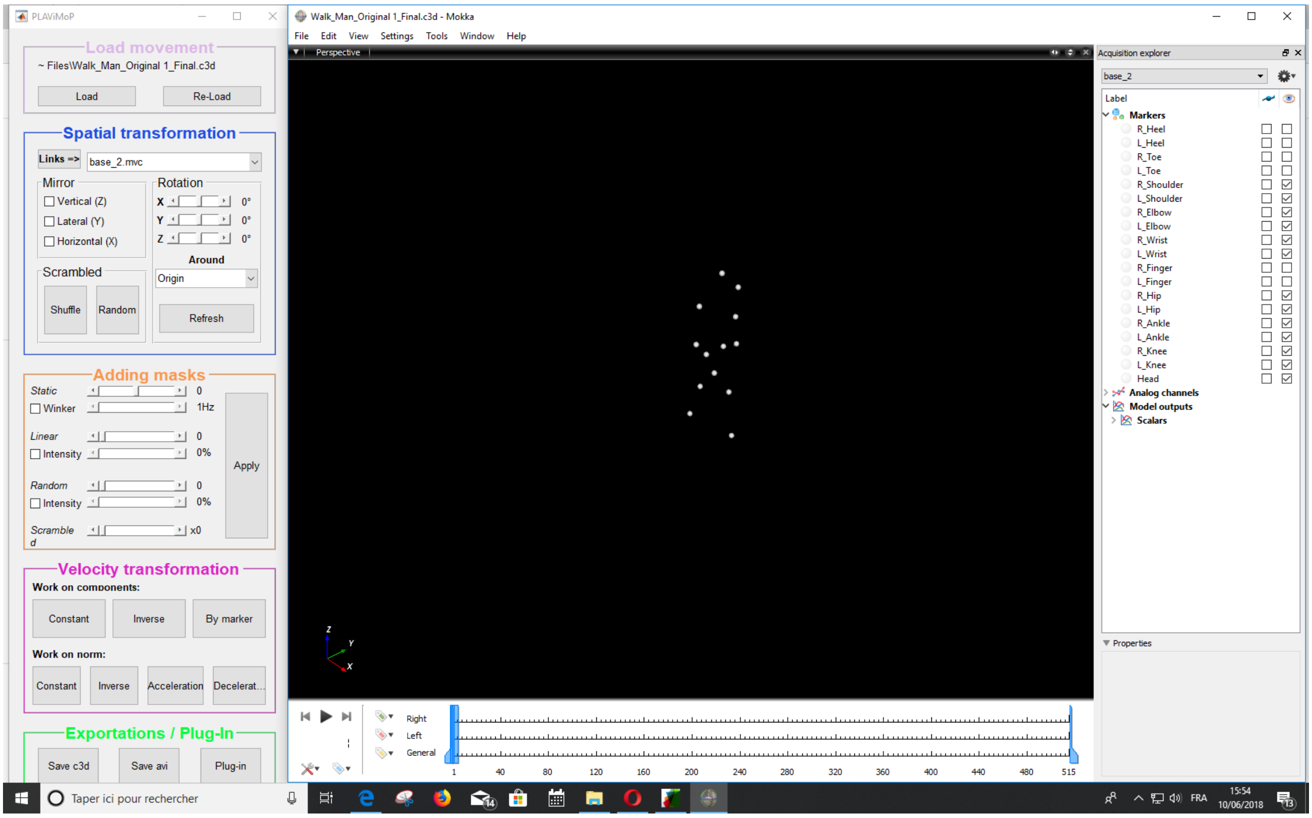


Figure 1: Global view of PLAViMoP. On the left, the different spatial, masking and kinematic transformations proposed by the application are presented. In the middle of the screen, the PLD visualization of the selected action is presented thanks to Mokka software (here, the static view of a walking man is presented). Note that the presence of grid floor can be added or removed to decrease the ambiguity of a 3D PLD shown on a 2D display. On the right side of the screen, available joints may be selected.

The application can be installed by downloading the software installation package directly from the following web address: http://plavimop.prd.fr. Both the MATLAB interface and Mokka software are required, as well as the Windows 64-bit system and an internet connection for PLAViMoP installation. The minimal screen resolution is 1024 x 900 pixels. However, the application has been optimized for a screen resolution of 1920 x 1080 pixels. Only the C3D format is supported by the PLAViMoP application. This format is the standard for the motion capture file[4]. The file should contain only 3D trajectories of a set of markers (e.g., no force plate data, no analogical channel). The X, Y and Z components are expressed in millimeters in a global reference frame (forward direction given by the x-axis, vertical direction given by the z-axis pointing upward and lateral direction given by the y-axis pointing to the left of the subject/object)[5]. The number of markers is not limited, but the common set of markers for human motion is listed in Table 1. The number of frames of the C3D file and the frame rate are not limited. However, a high number of frames and/or high frame rate will result in a time-consuming process. For example, standard C3D files are sampled at 100 Hz and contain approximately 200 frames.

Table 1: List and localization of common markers used to record human motions

Markers names		**Locations/Descriptions**
Right	**Left**	
R_Heel	L_Heel	*Back of the right and left heels*
R_Toe	L_Toe	*Top of the right and left big toes*
R_Ankle	L_Ankle	*Middle of external and internal ankle markers*
R_Knee	L_Knee	*Middle of external and internal knee markers*
R_Hip	L_Hip	*Right and left hips computed as centers of joints* (Weinhandl & O'Connor, 2010)
R_Shoulder	L_Shoulder	*Right and left acromions*
R_Elbow	L_Elbow	*Right and left lateral epicondyles*
R_Wrist	L_Wrist	*Right and left radial styloids*
R_Finger	L_Finger	*Distal phalanges of the right and left index fingers*
Head		*Mean point of right and left front head markers and right and left back head markers*

[4] For examples of the c3d file, please visit the following websites: http://www.rockthe3d.com/100-best-free-motion-capture-files/ and http://mocapclub.com/Pages/MonthlyMocap.htm. C3d files will be also disposal from April 2018 in our platform: http://plavimop.prd.fr.

[5] If you have PLD in another format, you can use the function "CSV2C3D" proposed as a plug-in in PLAViMoP Software. In this case, the .csv file should contain all information necessary to build C3D (3D time histories of markers, names of marker components and a time column).

The visualization of the PLD is achieved with Mokka (Figure 1, in the middle). The application directly allows the modification of some aspects of the PLD[6]. For example, Mokka can directly act on markers (e.g., size and color), PLD presentation (e.g., zoom and perspective), or time display (e.g., video cropping and playback speed).

The different transformations proposed by PLAViMoP can be accessed from the user interface situated at the left of the screen (Figure 1). The user interface is divided into five zones: load movement, spatial transformation, masking PLDs, velocity transformation, and exportations, which allow users to load a file containing a PLD, modify the file at the spatial level, add masking dots, modify the file at the kinematic level, and create a new PLD (as .c3d or .avi) after transformation, respectively.

Spatial transformations

At the spatial level, PLAViMoP enables users to spatially transform the original motion and add masking dots. The different modifications are detailed below. The transformation can be explained by stating that a C3D file consists of k frames sampled at F rate with a set of n markers whose time history coordinates are noted $\mathbf{M_j}(\boldsymbol{t}) \rightarrow \left\{M_j^x(t) \quad M_j^y(t) \quad M_j^z(t)\right\}^T$. The initial and final times are designated t_0 and t_f, respectively.

Modify the original PLD

Mirror transformation

This transformation enables users to create horizontal, lateral or vertical symmetry of the original motions (see Figure 2). The mathematical operations computed when selecting the mirror transformation buttons can be written as follows: $\forall\ j \in \{1 \dots n\}\ and\ \forall\ t \in \left\{t_0 \dots t_f\right\}$.

[6] Here, we describe only a few possible applications of Mokka. For an overview of all functionalities, please consult the help menu of Mokka, available at this address: http://biomechanical-toolkit.github.io/docs/Mokka/index.html

$$\mathbf{M}_{\mathbf{j}}(\mathbf{t})\left\{\begin{matrix} M_j^x(t) \\ M_j^y(t) \\ M_j^z(t) \end{matrix}\right\}\mathbf{M}_{\mathbf{j}}(\boldsymbol{t})\left\{\begin{matrix} -M_j^x(t) \\ M_j^y(t) \\ M_j^z(t) \end{matrix}\right\}\ (horizontal)$$

$$\mathbf{M}_{\mathbf{j}}(\mathbf{t})\left\{\begin{matrix} M_j^x(t) \\ M_j^y(t) \\ M_j^z(t) \end{matrix}\right\} \rightarrow \mathbf{M}_{\mathbf{j}}(\boldsymbol{t})\left\{\begin{matrix} M_j^x(t) \\ -M_j^y(t) \\ M_j^z(t) \end{matrix}\right\}(lateral)$$

$$\mathbf{M}_{\boldsymbol{j}}(\boldsymbol{t})\left\{\begin{matrix} M_j^x(t) \\ M_j^y(t) \\ M_j^z(t) \end{matrix}\right\} \rightarrow \mathbf{M}_{\mathbf{j}}(\boldsymbol{t})\left\{\begin{matrix} M_j^x(t) \\ M_j^y(t) \\ -M_j^z(t) \end{matrix}\right\}\ (vertical)$$

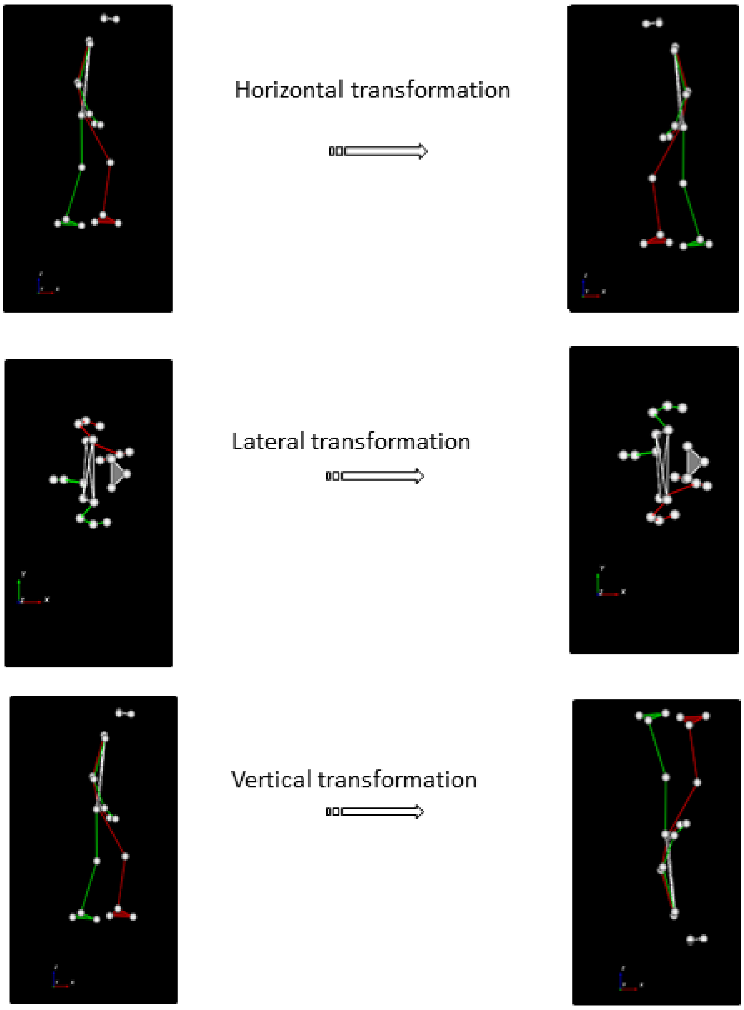


Figure 2: Static illustrations of the different mirror transformations (horizontal, lateral and vertical) in PLAViMoP. For the sake of clarity, left and right segments are represented in red and green, respectively.

Rotation transformation

The rotation transformation allows the original sequence of motion to rotate around different axes (x, y, z). The rotation point (origin, mean point or joints) and the rotation angle (from -180° to 180°) can be specified.

The available rotation points are the origin of the global reference frame $O \rightarrow \{0 \quad 0 \quad 0\}^T$, with each marker M_j and an average point N (mean point) computed as follows:

$$\mathbf{N(t)} = \begin{bmatrix} \frac{\sum_{j=1}^{n} M_j^x(t)}{n} \\ \frac{\sum_{j=1}^{n} M_j^y(t)}{n} \\ \frac{\sum_{j=1}^{n} M_j^z(t)}{n} \end{bmatrix}$$

Then, the rotation angles around the x, y, and z axes can be set with the corresponding sliders.

$\forall\, j \in \{1 \ldots n\}$ *and* $\forall\, t \in \{t_0 \ldots t_f\}$

$$\boxed{\mathbf{M_j(t)} = \mathbf{R}_{\gamma}^{t}\left(\mathbf{R}_{\beta}^{t}\left(\mathbf{R}_{\alpha}^{t}\left(\mathbf{M_j}(t) - [A^x(t_0) \quad A^y(t_0) \quad A^z(t_0)]^T\right)\right)\right) + [A^x(t_0) \quad A^y(t_0) \quad A^z(t_0)]^T}$$

where

$$\mathbf{R}_{\alpha}^{t} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha_{(t)}) & \sin(\alpha_{(t)}) \\ 0 & -\sin(\alpha_{(t)}) & \cos(\alpha_{(t)}) \end{bmatrix} ; \ \mathbf{R}_{\beta}^{t} = \begin{bmatrix} \cos(\beta_{(t)}) & 0 & -\sin(\beta_{(t)}) \\ 0 & 1 & 0 \\ \sin(\beta_{(t)}) & 0 & \cos(\beta_{(t)}) \end{bmatrix} ; \ \mathbf{R}_{\gamma}^{t} = \begin{bmatrix} \cos(\gamma_{(t)}) & \sin(\gamma_{(t)}) & 0 \\ -\sin(\gamma_{(t)}) & \cos(\gamma_{(t)}) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Importantly, in addition to the classical rotations used in the literature (i.e., rotation around the center of gravity of the z-axis; see Pavlova & Sokolov, 2000), PLAViMoP allows rotation around the x and y axes. Furthermore, not only rotations around the center of gravity but also rotations around any joint of the starting PLD are possible.

Scrambled transformation

This transformation allows the scrambling of each point constituting the sequence (e.g., Bidet-Ildei & Toussaint, 2015). There are two modes: **Shuffle** and **Random**.

In **Shuffle** mode, each point takes the place of another but conserves its initial trajectory and dynamic.

This transformation consists of replacing the initial coordinates of a marker M_j with those of another marker M_p. The indices of markers being exchanged are selected randomly.

$$\mathbf{M_j}(t) \rightarrow \mathbf{M}_{\boldsymbol{j}}(t) - \mathbf{M_j}(t_0) + \mathbf{M}_{\boldsymbol{p}}(t_0)$$

In **Random** mode, each point starts at a random spatial location but conserves its initial trajectory and dynamic. The starting position of each dot is chosen in order to keep the new trajectory inside the initial box of the original movement defined as follows:

$$\forall\, j \in \{1 \dots n\}\ and\ \forall\, t \in \{t_0 \dots t_f\} \rightarrow \mathbf{L} = \begin{bmatrix} min\left(M_j^x(t)\right) & max\left(M_j^x(t)\right) \\ min\left(M_j^y(t)\right) & max\left(M_j^y(t)\right) \\ min\left(M_j^z(t)\right) & max\left(M_j^z(t)\right) \end{bmatrix} = \begin{bmatrix} L_{min}^x & L_{max}^x \\ L_{min}^y & L_{max}^y \\ L_{min}^z & L_{max}^z \end{bmatrix}$$

Appendix 2 details the control loop that maintains the point-lights inside the initial box after the transformation.

Add mask to the PLD

The masks are additional point lights added to the original movement (Cutting et al., 1988). With PLAViMoP, it is possible to add the following four types of masks to the original PLD sequence: static masks, linear masks, random masks, and scrambled masks.

Static mask

A static mask is simply a stationary set of point lights whose coordinates (randomly defined) lie within the limits of the bounding box. Anywhere from 1 up to 200 static masks can be added using a slider. These points can be purely static or flashing. The flashing frequency can be set from 1 to 25 Hz. Since the C3D file frame rate is 100 Hz, a flashing frequency of 1 Hz causes a mask to be alternately visible and invisible during sets of 25 consecutive frames, while a flashing frequency of 25 Hz causes a mask to be alternately visible and invisible during sets of 2 consecutive frames.

Linear mask

A linear mask is a moving point light with constant velocity. Linear masks only move along the x-axis (in a positive or negative direction). Their initial positions are randomly chosen. According to their initial positions and the duration of the C3D file, a maximal velocity is computed to keep the masks within the limits of the bounding box. Then, a random percentage of this velocity is chosen to compute the trajectory. Up to 200 static masks can be added using the dedicated slider. Moreover, it is possible to control the velocity of each masking point (from 0 % to 100 %). Since there are two possible directions for the displacement of linear masks, masks can be divided into two groups. All markers for the same group will have the same velocity. An intensity of 0 % causes static masks, while 100 % intensity ensures that all markers of the group stay within the limits of the bounding box (see Appendix 3 for the algorithm).

Random mask

A random mask is composed of point lights with a randomly defined trajectory. Both the initial position and instantaneous acceleration are randomly chosen. Masks move along all three axes. A control loop ensures that all points constituting the mask stay within the bounding box limits (rebound). As mentioned previously, it is possible to specify the common percentage of maximal velocity (arbitrarily fixed to 10 m/s) assigned to each masking dot (from 0 % to 100 %). The algorithm is detailed in Appendix 4.

Scrambled mask

A scrambled mask is a set of point lights with the same trajectory of the initial point-light set. Only their starting positions are defined randomly (Bidet-Ildei et al., 2010). A control loop ensures that the mask stays within the bounding box limits. The number of scrambled masks (k) is proportional to the number of point lights (n) in the initial set. Note that k is limited by the following relation: $k \times n < 200$.

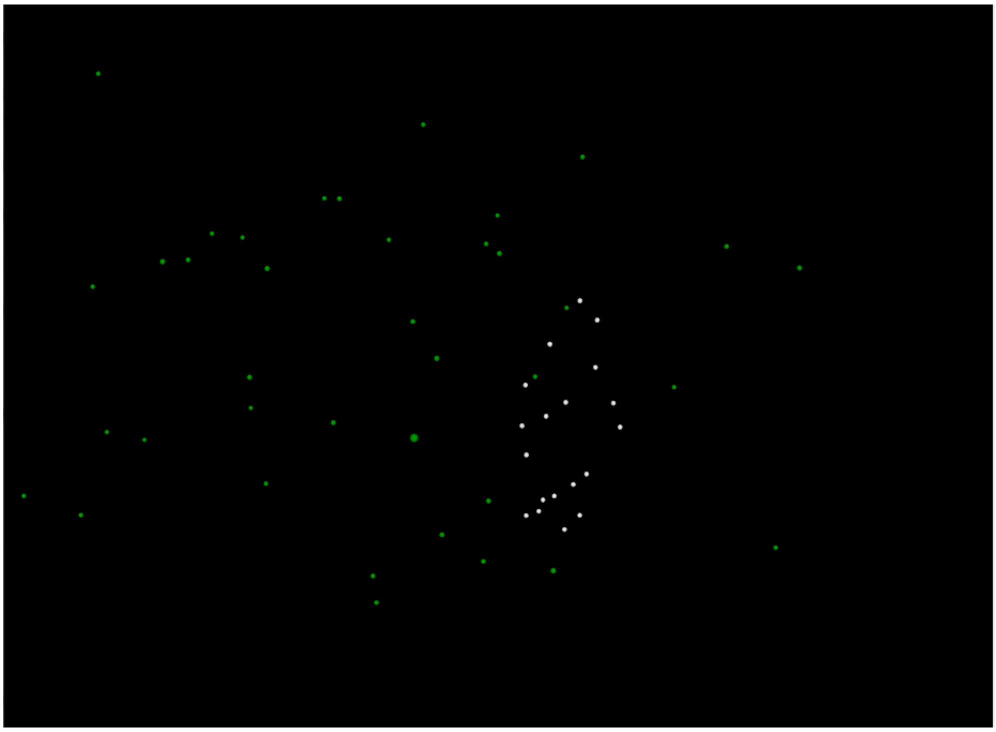


Figure 3: Static illustration of the addition of a scrambled mask (dots in green) to a PLD (dots in white) sequence. Here, we added 2 duplications for each point in the initial PLD sequence.

<u>Kinematic transformations</u>

This series of tools aims to modify the dynamic of point-light displacement. There are two different types of transformations:

- Norm of the velocity: in this case, the norm of the velocity of a point light is modified in order to maintain the original point-light path (Bidet-Ildei et al., 2008; Martel et al., 2011).
- Components of the velocity: in this case, the norm, components and path are modified (Elsner, Falck-Ytter, & Gredeback, 2012).

Importantly, whereas some authors have already developed tools to modify the dynamics of PLDs (as for example frame scrambling, see van Boxtel & Lu, 2013), to our knowledge, no tool allows to automatically modify the dynamics of the motion without changing the spatial trajectory or to modify independently each component of the motion.

Kinematic transformations based on changes in the norm

The norm of the velocity of a given point of light is classically computed at each frame with:

$$\|V\| = \sqrt{V_X^2 + V_Y^2 + V_Z^2}$$

All transformations detailed below allow the modification of the dynamics of the original sequence while maintaining the original trajectory and movement duration. One can apply each transformation to one or several markers at the same time. The velocity (V) and acceleration (A) of each point light are visible under the Scalars section of Mokka and can be easily exported to a .csv file with Mokka.

Constant norm

For this transformation, the components of a given point-light velocity are modified in order to achieve the following:

1) Keep the original point-light path.
2) Keep the original movement duration.
3) Keep a constant norm of the given point-light velocity throughout the movement.

To achieve this, the following process is used:

1) The length of the path is computed:

$$L = \sum_{i=t_0}^{t_f-1} \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2 + (Z_{i+1} - Z_i)^2}$$

2) To travel the path entirely, a mean velocity is computed, taking into account the duration of the movement:

$$\|\bar{V}\| = \frac{L}{t_f - t_0}$$

3) Let dt be the duration between two consecutive frames; the average distance between each pair of frames can be computed:

$$d = \|\bar{V}\| * dt$$

4) Then, the tangent unit vector (**T**) of the Frenet-Serret frame of the original path between the current frame and the next frame is computed.

5) The modified trajectory is initialized with the original coordinates of the point light:

$$\begin{bmatrix} X_{t_0} \\ Y_{t_0} \\ Z_{t_0} \end{bmatrix}$$

6) The next coordinates of the modified point light are finally computed as follows:

$$\begin{bmatrix} X_{t_i} \\ Y_{t_i} \\ Z_{t_i} \end{bmatrix} = \begin{bmatrix} X_{t_{i-1}} \\ Y_{t_{i-1}} \\ Z_{t_{i-1}} \end{bmatrix} + \mathbf{T} * \mathrm{d}$$

As illustrated in Figure 4, the constant transformation modifies the different components of velocity to have a constant norm but maintains the original path of the point light. Interestingly, the zoom (Figure 4C right) highlights that the point light travels the same path but does not reach each point of the path at the same time as before the transformation.

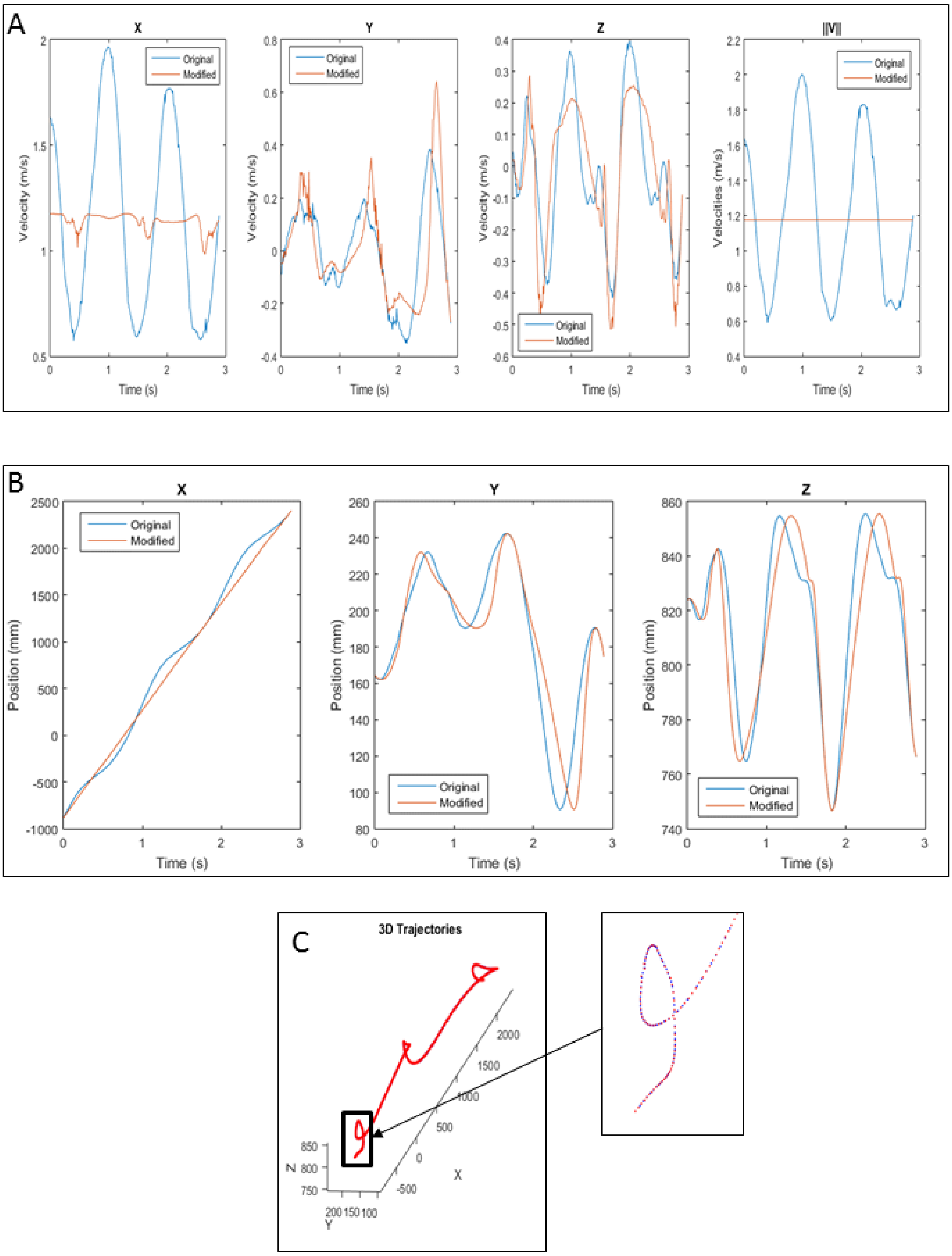


Figure 4: Graphic illustration of the constant norm transformation. A) Tangential velocity observed on each component and on the norm before (in blue) and after (in red) the transformation. B) Spatial position of each component before (in blue) and after (in red) the transformation. C) 3D trajectories before (in blue) and after (in red) the transformation.

Inverse norm

For this transformation, the components of a given point-light velocity are modified in order to achieve the following:

1) Keep the original point-light path.
2) Keep the original movement duration.
3) Obtain a norm of the given point-light velocity inverted with respect to the mean norm original velocity.

To achieve this, the following process is used:

1) The length of the path is computed:

$$L = \sum_{i=t_0}^{t_f-1} \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2 + (Z_{i+1} - Z_i)^2}$$

2) The mean norm velocity $\|\bar{V}\|$ is obtained by:

$$\|\bar{V}\| = \frac{\sum_{i=1}^{nFrames} \|V_{(t)}\|}{nFrames}$$

3) The instantaneous inverted norm velocity $\|V_t^{inv}\|$ is computed as follows:

$$\|V_t^{inv}\| = 2 * \|\bar{V}\| - \|V_{(t)}\|$$

4) As it is possible to obtain a negative instantaneous inverted norm velocity, a control loop has been written. There are two steps. The first step is to increase each value of $\|V_t^{inv}\|$ so that the minimum value is higher than 0:

$$if\ \min(\|V_t^{inv}\|) < 0\ then\ \|V_t^{inv}\| = \|V_t^{inv}\| - \min(\|V_t^{inv}\|)$$

The second step consists of adjusting the corrected inverted norm velocity in order to guarantee a maximal difference between the original final position and the modified final position of less than 2 mm (see Appendix 5).

5) Let dt be the duration between two consecutive frames. The average distance between each pair of frames can be computed as follows:

$$d = \|V_t^{inv}\| * dt$$

6) Then, the tangent unit vector (**T**) of the Frenet-Serret frame of the original path between the current frame and the next frame is computed.

7) The modified trajectory is initialized with the original coordinates of the point light:

$$\begin{bmatrix} X_{t_0} \\ Y_{t_0} \\ Z_{t_0} \end{bmatrix}$$

8) The next coordinates of the modified point light are finally computed as follows:

$$\begin{bmatrix} X_{t_i} \\ Y_{t_i} \\ Z_{t_i} \end{bmatrix} = \begin{bmatrix} X_{t_{i-1}} \\ Y_{t_{i-1}} \\ Z_{t_{i-1}} \end{bmatrix} + \mathbf{T} * \mathrm{d}$$

Accelerated norm

For this transformation, the components of a given point-light velocity are modified in order to achieve the following:

1) Keep the original point-light path.
2) Keep the original movement duration.
3) Obtain a uniformly accelerated motion.

To achieve this transformation, we followed the process detailed below:

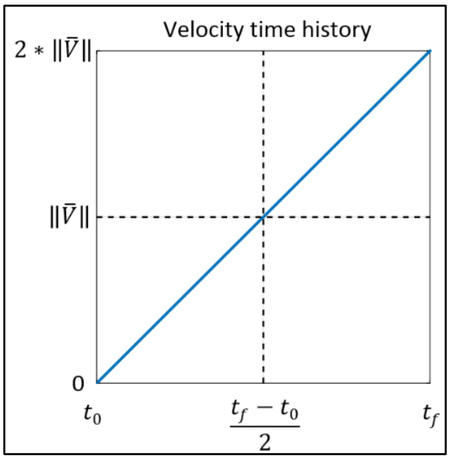
1) The length of the path is computed:

$$L = \sum_{i=t_0}^{t_f-1} \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2 + (Z_{i+1} - Z_i)^2}$$

2) The mean norm velocity $||\bar{V}||$ is obtained by:

$$||\bar{V}|| = \frac{L}{t_f - t_0}$$

3) Then, the velocity profile $V_{(t)}$ is set as:



4) Let dt be the duration between two consecutive frames. The average distance between each pair of frames can be computed:

$$d = V_{(t)} * dt$$

5) The tangent unit vector (**T**) of the Frenet-Serret frame of the original path between the current frame and the next frame is computed.

6) The modified trajectory is initialized with the original coordinates of the point light: $\begin{bmatrix} X_{t_0} \\ Y_{t_0} \\ Z_{t_0} \end{bmatrix}$

7) The next coordinates of the modified point light are finally computed as follows:

$$\begin{bmatrix} X_{t_i} \\ Y_{t_i} \\ Z_{t_i} \end{bmatrix} = \begin{bmatrix} X_{t_{i-1}} \\ Y_{t_{i-1}} \\ Z_{t_{i-1}} \end{bmatrix} + \mathbf{T} * \mathrm{d}$$

Decelerated norm

For this transformation, the components of a given point-light velocity are modified in order to achieve the following:

1) Keep the original point-light path.

2) Keep the original movement duration.

3) Obtain a uniformly decelerated motion.

To achieve this transformation, we followed the process detailed below:

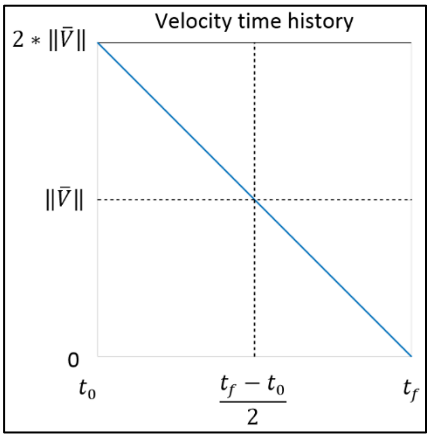
1) The length of the path is computed:

$$L = \sum_{i=t_0}^{t_f-1} \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2 + (Z_{i+1} - Z_i)^2}$$

2) The mean norm velocity $||\bar{V}||$ is obtained by:

$$||\bar{V}|| = \frac{L}{t_f - t_0}$$

3) Then, the velocity profile $V_{(t)}$ is set as:



4) Let dt be the duration between two consecutive frames. The average distance between each pair of frames can be computed:

$$d = V_{(t)} * dt$$

5) The tangent unit vector (**T**) of the Frenet-Serret frame of the original path between the current frame and the next frame is computed.

6) The modified trajectory is initialized with the original coordinates of the point light:

$$\begin{bmatrix} X_{t_0} \\ Y_{t_0} \\ Z_{t_0} \end{bmatrix}$$

7) The next coordinates of the modified point light are finally computed as follows:

$$\begin{bmatrix} X_{t_i} \\ Y_{t_i} \\ Z_{t_i} \end{bmatrix} = \begin{bmatrix} X_{t_{i-1}} \\ Y_{t_{i-1}} \\ Z_{t_{i-1}} \end{bmatrix} + \mathbf{T} * \mathrm{d}$$

Transformations applied to each component of the velocity

These transformations can be applied component by component and point light by point light. Three transformations are available: constant, inverse and manual. Each transformation can be accessed easily with the use of the popup menu on top of each column of graphs (see Figure 5). Once a transformation is chosen for a point light and a velocity component, the new acceleration and coordinates are automatically computed. All the transformations are retained and definitively applied to the C3D file when closing the window. Consequently, it is not necessary to close the window after each point-light transformation.

As for the transformations applied to the norm of the velocity, when the C3D file is updated, the new velocity and acceleration components and norms are written and can be recorded in a .csv file.

Constant transformation

The process is divided into six steps:

1) Keep initial (V_{t_0}) and final (V_{t_f}) velocity components.

2) The mean velocity component $\|\bar{V}\|$ is obtained by:

$$\|\bar{V}\| = \frac{\sum_{i=1}^{nFrames}\|V_{(i)}\|}{nFrames}$$

3) Set the new velocity component to $\|\bar{V}\|$ from 5 % and 95 % of the movement.
4) Then, a shape-preserving piecewise cubic interpolation is performed from 0 % - 5 % and from 95 % - 100 % of the movement in order to "connect" (V_{t_0}) and (V_{t_f}) to $\|\bar{V}\|$
5) Compute coordinates and acceleration.
6) Use a control loop to guarantee a final gap between the original and modified point-light coordinates of less than 0.1 mm.

Inverse transformation

The process is divided into two steps:

1) The mean velocity component $\|V\|$ is obtained by:

$$\|\bar{V}\| = \frac{\sum_{i=1}^{nFrames}\left\|V_{(i)}\right\|}{nFrames}$$

2) The instantaneous inverted velocity component is then computed as follows:

$$\left\|V_t^{inv}\right\| = 2 * \|\bar{V}\| - \left\|V_{(t)}\right\|$$

Manual transformation

Manual transformation allows for the redefinition of the shape of the velocity component curve. For a C3D file of more than 20 frames, 19 movable points are added to the velocity curve (see Figure 5, green circles). To move the checkpoint, users can left click, hold and vertically drag the circle. When the left button is released, the velocity and acceleration components and the point-light coordinates are re-computed. As shown in Figure 5, shape-preserving piecewise cubic interpolation is performed between the clicked circle and the previous green (or red, if applicable) circle and between the clicked circle and the next green (or red, if applicable) circle.

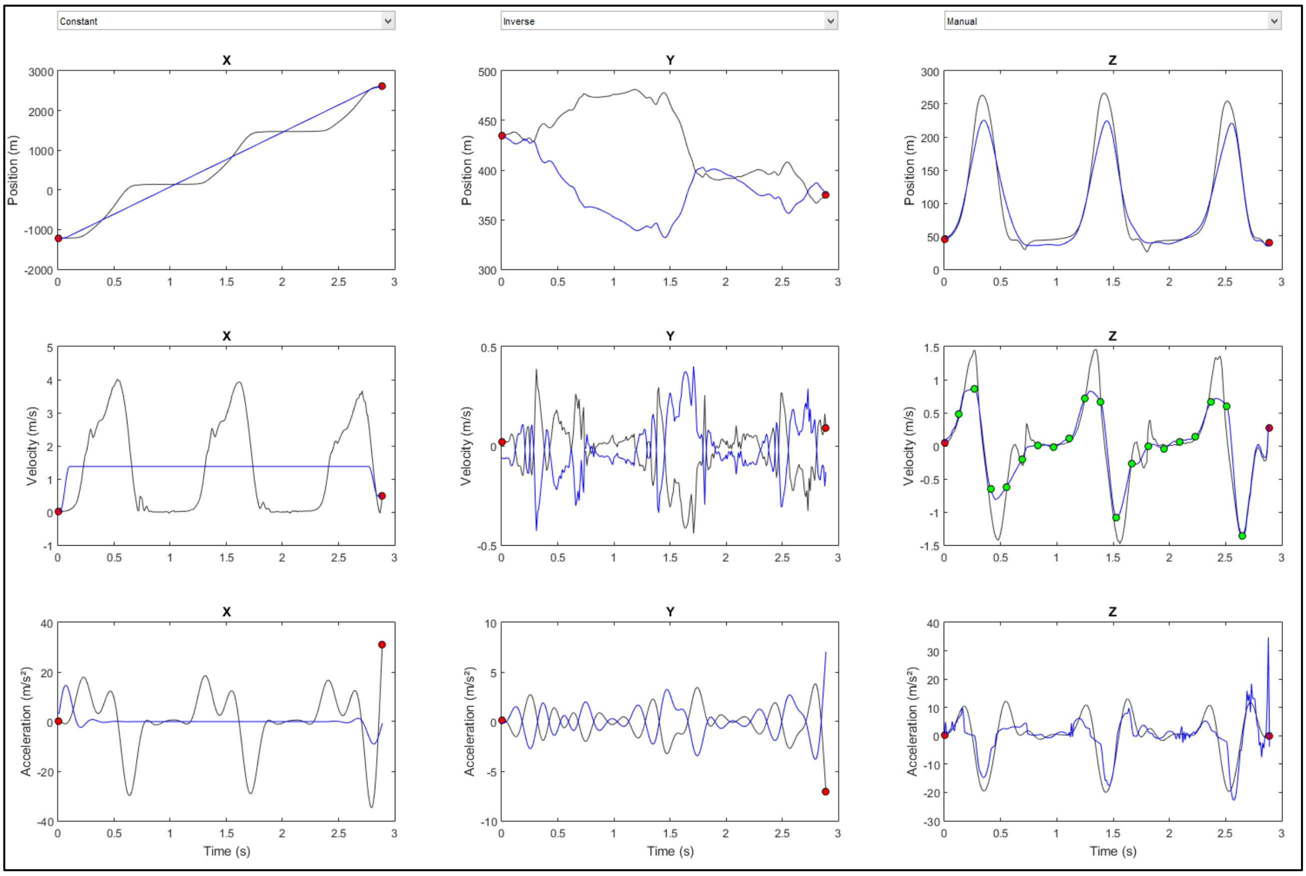


Figure 5: Illustration of the three types of transformations applicable for each component for one point light. The x-velocity component is constrained to be constant throughout the movement, while the y-velocity component is inverted, and the z-velocity component is set manually. For each transformation, position, velocity and acceleration are directly visible. Black lines represent the original movement, and blue lines represent the modified movement.

Discussion and Conclusion

As described by several authors, “visual processing of biological motion produced by living organisms is of immense value for successful daily life activities and, in particular, for adaptive social behavior and nonverbal communication (p. 981)” (Pavlova, 2012). For more than forty years, numerous studies have sought to better understand the mechanisms involved in this process, especially by studying the consequences of spatial or kinematic transformation in perceptual competencies.

PLAViMoP is a new program that enables users to visualize and transform 3D point-light sequences. The innovation of this software presents several advantages for research and its applications.

First, thanks to this software, classical transformations of spatial (e.g., modifying the orientation, adding masking dots, and scrambling the original motion) and kinematic (e.g., changing the norm of the velocity) characteristics of PLD can be standardized using specific algorithms. This advance is important for scientists working on PLD sequences because it offers the possibility to work with similar stimuli. Actually, by disambiguating some transformations such as the application of scrambled modifications or the point of origin of a rotation, PLAViMoP will facilitate the reproducibility of the data, a crucial methodological step toward a better understanding of the literature on the mechanisms sustaining PLD processing. Moreover, PLAViMoP allows the application of these transformations in 3D sequences and presents new types of spatial and kinematic transformations (i.e., the spatial rotation of original PLDs for each limb constituting the sequence, the possibility of rotating the original PLD on the different axes [x, y or z], or the possibility of separately modifying the kinematics of each component of the original PLD). These new functionalities introduce the possibility of better understanding the crucial characteristics that are involved in the recognition of PLD. Futures studies should be performed to assess the effects of these different transformations. Both perceptual consequences of these transformations (recognition, detection, discrimination of the movement) and their implications in other cognitive or social functions (do these transformations modify the link between motion perception and processing of language, numbers, or social activity?) should be investigated. Brain studies will also be valuable to investigate whether these transformations modify brain networks classically observed in the perception of biological motion. PLAViMoP software facilitates the implementation if these experiments because it allows to produce a series of .avi files which corresponds exactly to the settings made in PLAViMoP software (color and size of dots, point of view, orientation, kinematics, ect.). After, these videos files can be easily use with the Psychtool box of Matlab (http://psychtoolbox.org/), ePrime (https://pstnet.com/welcome-to-e-prime-2-0/) or PsychoPy (http://www.psychopy.org/) programs to design experiments. For example, using PLAViMoP software, we recently created 125 videos and we designed 4 experiments with Eprime 2 to assess how motion characteristics (orientation and kinematics) can influence the link between action and language (Beauprez & Bidet-Ildei, 2018). For information, all the stimuli used in these experiments are freely available in PLAViMoP platform (http://plavimop.prd.fr/news/the-kinematics-not-the-orientation-of-an-action-influences-language-processing).

Second, PLAViMoP will allow the use of the point-light display technique not only to study perceptual competencies but also to set up observational learning protocols. In fact, the efficacy of observing someone performing the task to be learned is well documented in motor learning (see Gatti et al., 2013; Vogt & Thomaschke, 2007; Wolpert, Diederichsen, & Flanagan, 2011, for reviews). Interestingly, the beneficial effects of observation prior to physical practice also appear when actions are presented from real or point-light videos (e.g., Horn et al., 2002; Hayes et al., 2007a). However, understanding the processes underlying observational learning generally requires video transformation, such as characteristics of the model's performance (e.g., Andrieux & Proteau, 2014; Blandin, Lhuisset & Proteau, 1999; Rohbanfard & Proteau, 2011) and its stability across trials (e.g., Buchanan & Dean, 2014). Other common procedures require displaying naturalistic or constant limb velocity (e.g., Roberts, Bennett, Elliot & Hayes, 2015) or limb or joint occlusion (e.g., Hayes et al., 2007b; Mulligan, Lohse & Hodges, 2016; Mann, Abernethy, Farrow, Davis & Spratford, 2010) to determine which component of an action is essential to the learning processes. With the spatial and kinematic transformations included, PLAViMoP is a powerful tool that can be used for a better understanding of observational learning processes.

With a more applied focus, researchers have demonstrated the effectiveness of action observation in motor performance and motor rehabilitation, as well as in the treatment of language disorders. For example, to learn complex motor skills involved in volleyball (Weeks & Anderson, 2000), football (Horn et al., 2002), cricket bowling (Breslin, Hodges, & Williams, 2009) or golf (D'Innocenzo, Gonzalez, Williams, & Bishop, 2016), observing someone performing the action to be practiced enhances learning. Furthermore, observational learning has also been demonstrated to be efficient in the rehabilitation of patients suffering from motor disorders (see Abbruzzese, Avanzino, Marchese, & Pelosin, 2015 for a review) and in the recovery of postsurgical orthopedic intervention (Bellelli, Buccino, Bernardini, Padovani, & Trabucchi, 2010; Park, Song, & Kim, 2014). Therefore, the systematic observation of daily actions, followed by their execution, becomes a rehabilitative strategy to accelerate the functional recovery in patients with motor impairment (Ertelt et al., 2007). Finally, based on the action-language link (see Fischer & Zwaan, 2008; Pulvermüller, 2005; Willems & Hagoort, 2007 for reviews), it has been shown that rehabilitation based on the observation of actions efficiently aids the recovery of word forms in aphasic patients (Marangolo et al., 2010; see Ertelt & Binkofski, 2012 for a review).

However, the recording of videos is often difficult in professional situations that do not always have the materials necessary for motion capture. Moreover, even if they have access to a video recording system, the videos generally represent the motions as produced, i.e., without transformation. PLAViMoP allows therapists and coaches to modify the original videos to accentuate the processing of motion or to complicate or simplify the motion perceived. This feature could have a specific application to motor learning, to improve both global and specific learning and to optimize transfer (Robin, Toussaint, Blandin, & Proteau, 2005). Moreover, this software makes it possible to examine the evolution of patients' motor capacities. For example, if a patient has undergone a knee operation, the "observation therapy" could initially be based on videos of movements with the knee blocked on the 3 axes; each axis of motion could then gradually be unlocked to portray the evolving possibilities for patients' motor production (Moon, Robson, Langari, & Buchanan, 2012, 2015).

In conclusion, PLAViMoP software is the first free program which allow to visualize and transform PLDs without the need for competences in computer programming. It will undoubtedly facilitate the replication of scientific data. It will also allow professionals (teacher in adapted physical activities, sports trainer, ect.) to access to the point-lights displays technique that could be used for learning new sporting gestures, developing perceptual anticipation skills or rehabilitating patients with motor disorders. Future steps will consist to enrich the functionalities using plug-in and to develop the program for other operating system.

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Appendix 1: Experimental papers using PLD transformations integrated into PLAViMoP. Here, we present only studies performed on humans.

PLAViMoP transformations used in the literature	In children (0 to 9 years)	In young adults (18 to 30 years)	In the elderly (61 to 78 years)	In pathology
	Spatial transformations of PLD			
Rotation on Z axis	(Bardi et al., 2011; Bardi, Regolin, & Simion, 2014; Bertenthal, Proffitt, & Cutting, 1984; Bertenthal, Proffitt, & Kramer, 1987; Bertenthal, Proffitt, Spetner, & Thomas, 1985; Galazka, Roché, Nyström, & Falck-Ytter, 2014; Reid, Hoehl, & Striano, 2006; Simion et al., 2008; Yoon & Johnson, 2009)	(Chang & Troje, 2008; Clarke et al., 2005; Daems & Verfaillie, 1999; Dittrich, 1993; Dittrich et al., 1996; Grossman, Battelli, & Pascual-Leone, 2005; Grossman & Blake, 2001; Hiris, Krebeck, Edmonds, & Stout, 2005; Neri & Levi, 2007; Orban de Xivry, Coppe, Lefevre, & Missal, 2010; Pavlova & Sokolov, 2000, 2003; Pinto & Shiffrar, 1999; Shipley, 2003; Sumi, 1984; Troje & Westhoff, 2006)	(Legault, Troje, & Faubert, 2012; Pilz, Bennett, & Sekuler, 2010; Spencer, Sekuler, Bennett, Giese, & Pilz, 2016).	**Children with autism** (Klin et al., 2009)
Scrambled PLD	(Bardi et al., 2011; Bertenthal et al., 1984, 1985; Bidet-Ildei et al., 2014; Freire, Lewis, Maurer, & Blake, 2006; Hirai & Hiraki, 2005)	(Anderson et al., 2013; Bidet-Ildei & Toussaint, 2015; Chang & Troje, 2008, 2009; Freire et al., 2006; Garcia & Grossman, 2008; Grossman et al., 2000, 2005; Grossman & Blake, 2002; Hiris, Krebeck, et al., 2005; Ikeda, Blake, & Watanabe, 2005; Jokisch, Daum, Suchan, & Troje, 2005; Orban de Xivry et al., 2010; Pavlova et al., 2015; Peelen, Wiggett, & Downing, 2006; Peuskens, Vanrie, Verfaillie, & Orban, 2005; Saunier et al., 2013; Saygin et al., 2004; Thurman & Lu, 2014; Ulloa & Pineda, 2007)	(Spencer et al., 2016)	**Children with autism** (Kaiser et al., 2010) **Adolescents with autism** (Cusack, Williams, & Neri, 2015; Freitag et al., 2008) **Adults with autism** (Nackaerts et al., 2012b) **Adults with obsessive-compulsive disorder** (Jung et al., 2009) **Adults with schizophrenia**

				(J. Kim, Doop, Blake, & Park, 2005)
Horizontal Mirror	(Galazka et al., 2014)	(Clarke et al., 2005)		
	Masking PLD			
Scrambled mask		(Bertenthal & Pinto, 1994; Bidet-Ildei et al., 2010, 2016; Bidet-Ildei, Gimenes, Toussaint, Beauprez, & Badets, 2017b; Bidet-Ildei, Sparrow, et al., 2011; Chandrasekaran, Turner, Bülthoff, & Thornton, 2010; Cutting et al., 1988; Hiris, Humphrey, & Stout, 2005; Ikeda et al., 2005; Pinto & Shiffrar, 1999; Thornton et al., 1998; Troje & Westhoff, 2006)		**Adolescents born preterm presenting periventricular lesions** (Pavlova, Bidet-Ildei, Sokolov, Braun, & Krageloh-Mann, 2009; Pavlova, Staudt, Sokolov, Birbaumer, & Krageloh-Mann, 2003)
Random mask		(Chang & Troje, 2008; Cutting et al., 1988; Hiris, 2007; Thornton et al., 1998; Thornton, Rensink, & Shiffrar, 2002)	(Pilz et al., 2010)	
Linear mask		(Cutting et al., 1988)		**Adolescents with autism** (Koldewyn, Whitney, & Rivera, 2009)
	Kinematic transformations of PLD			
Constant norm		(Beauprez & Bidet-Ildei, 2018; Martel et al., 2011; Stadler, Springer, Parkinson, & Prinz, 2012)		
Inverse norm	(Meary, Kitromilides, Mazens, Graff, & Gentaz, 2007)	(Badets et al., 2015; Beauprez & Bidet-Ildei, 2018; Bidet-Ildei et al., 2008, 2006; Martel et al., 2011; Pozzo et al., 2006)		
Accelerating norm		(Martel et al., 2011)		
Constant velocity on X, Y and Z		(Elsner et al., 2012)		

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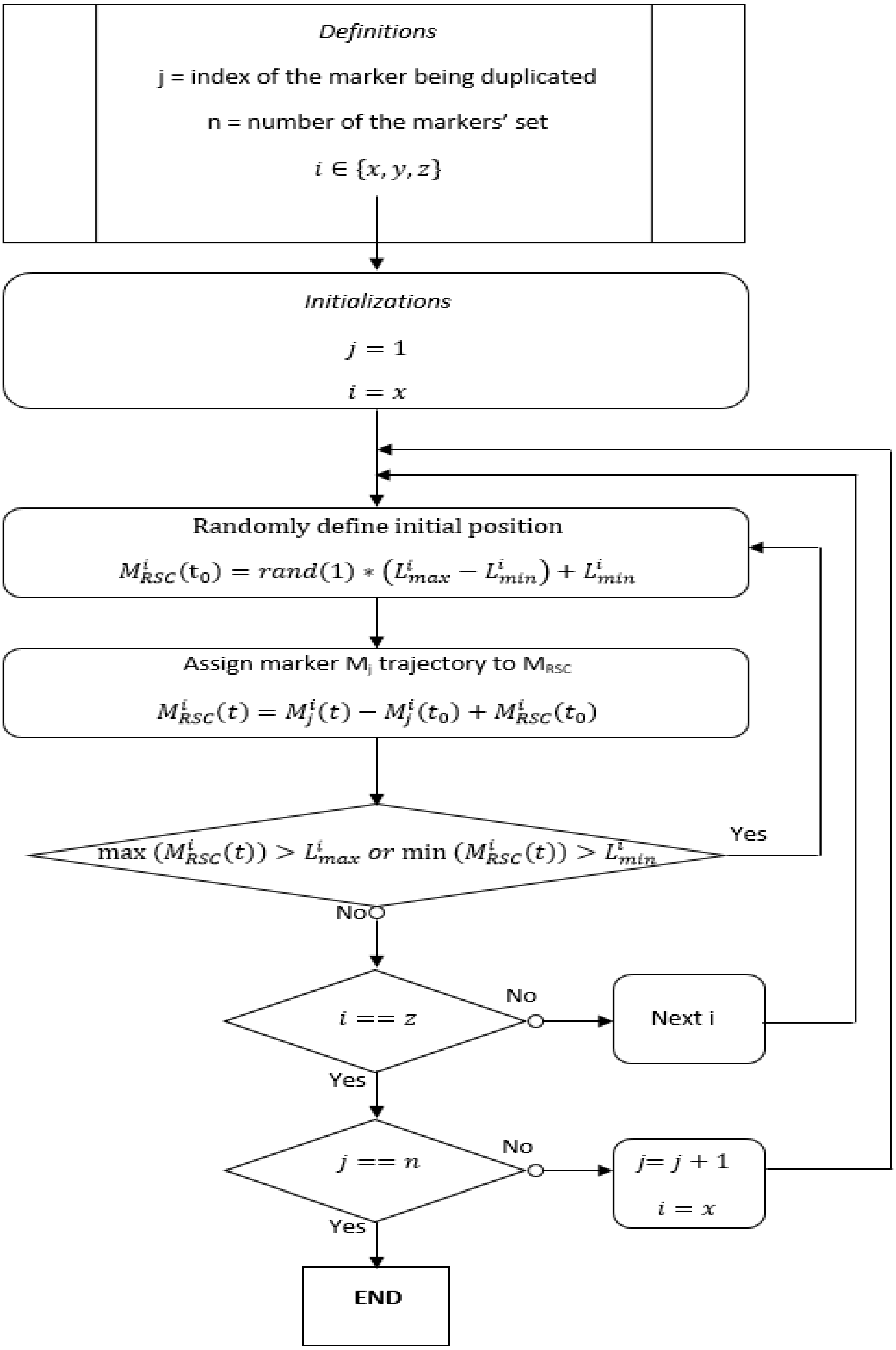
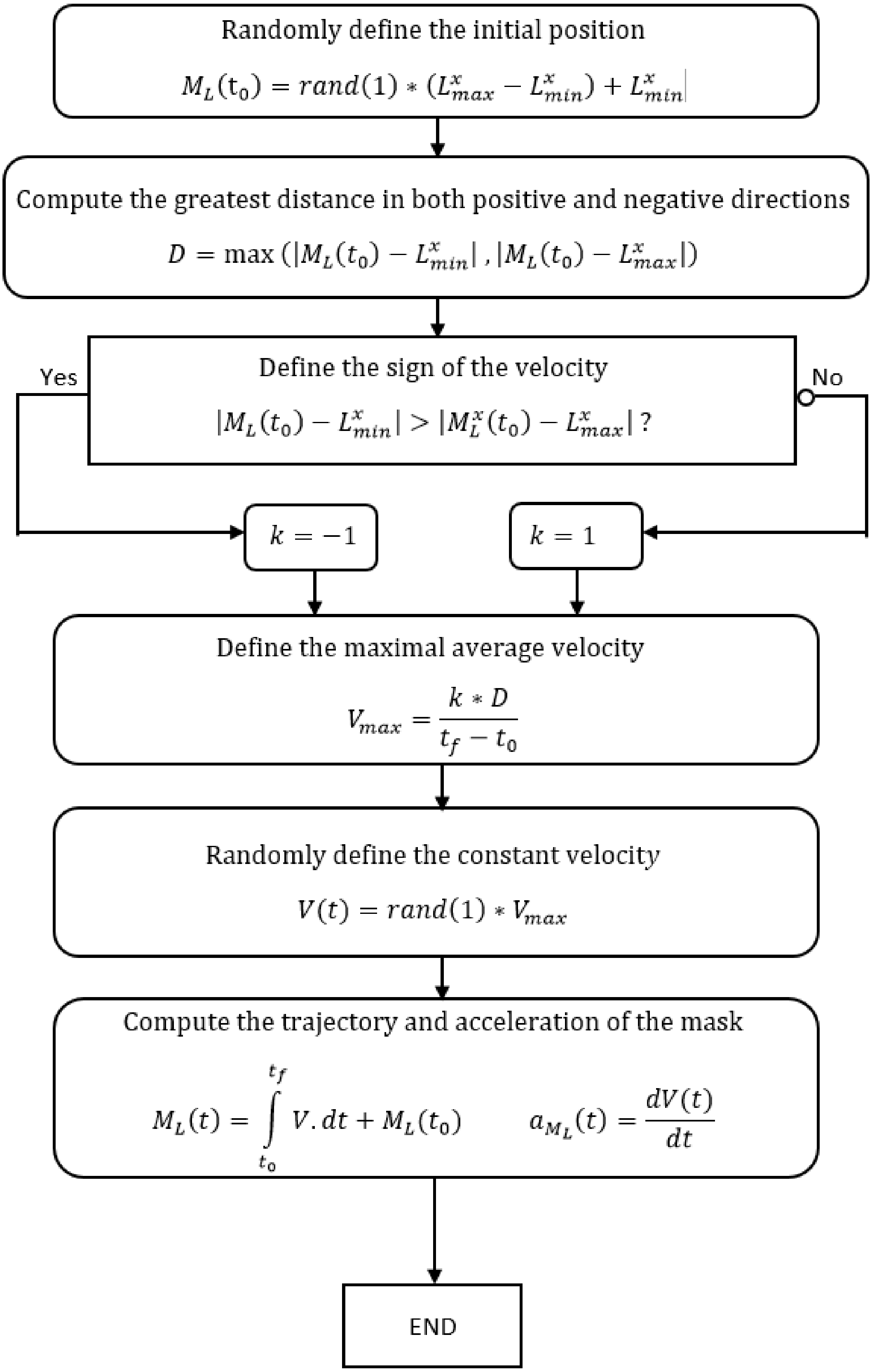
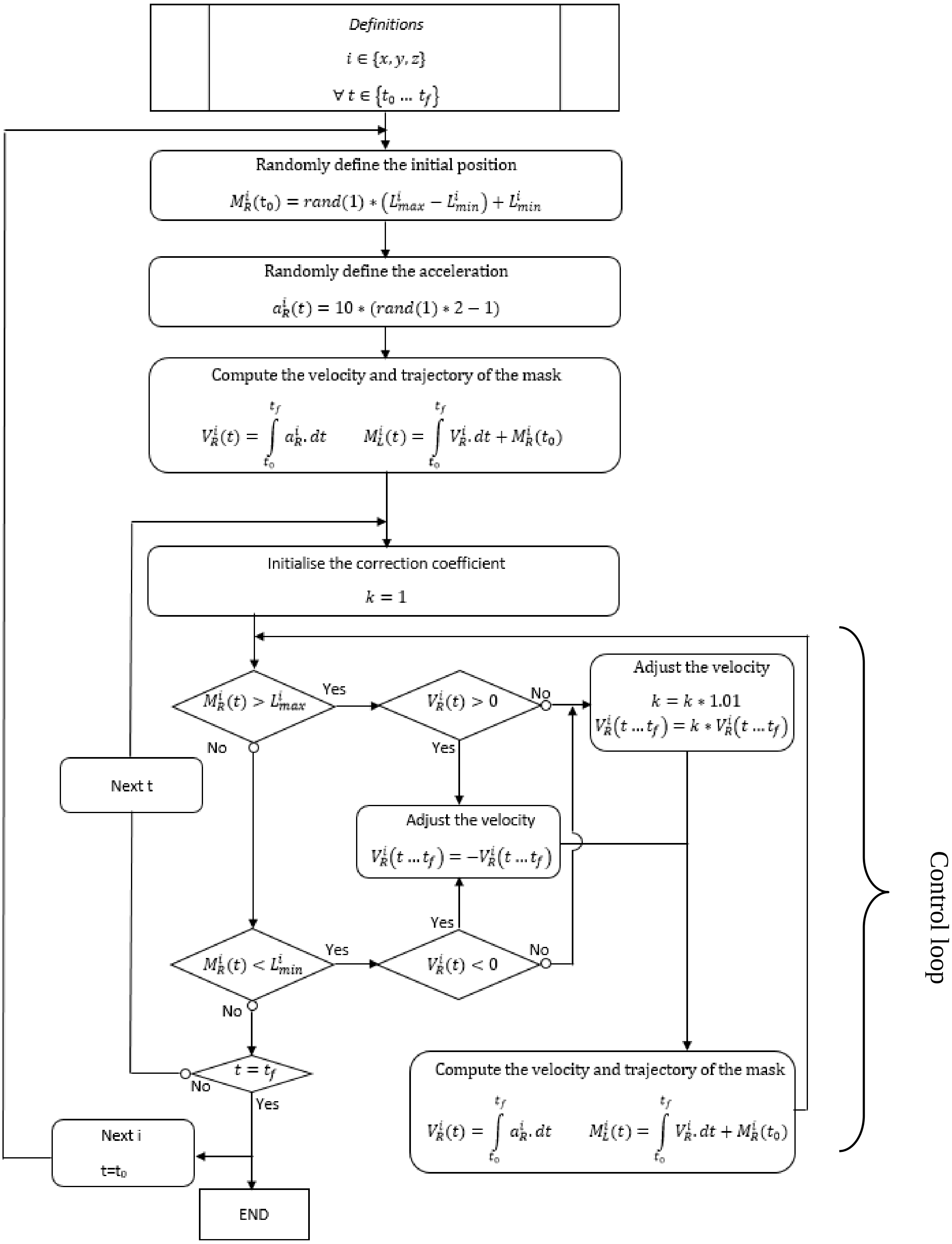
APPENDIX 2: Control loop that maintains the point-lights inside the initial box after the random transformation of PLDs.



Appendix 3: Algorithm used to create linear masking dots.



Appendix 4: Algorithm used to create random masking dots.



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Appendix 5: Algorithm used to inverse the norm of the velocity