On the use of Kinetography Laban to notate robot action and motion

Paolo Salaris, Naoko Abe and Jean-Paul Laumond

***Abstract*—Roboticists aim at segmenting robot actions into a sequence of motion primitives in order to simplify the robot programming phase. Choreographers aim at capturing the essence of human body movements within a sequence of symbols that can be understood by dancers. To that extent, roboticists and choregraphers pursue the same quest. This paper reports a pluridisciplinary approach combining a dance notation system (the Kinetography Laban) with a robot programming system (the Stack of Task). Motion scores are used instead of quantitative data to compare and enlighten differences in robot and human movements. We then discuss about plausible origins of these differences taking into account the implicit rules of the Kinetography Laban on how a movement is executed by humans. This comparison, in the light of the Kinetography Laban, opens some challenging questions related to motion segmentation and motion naturalness.**

I. Introduction: Dance Notation and Robot Motion

A. *Motion writing*

How to park a car? A way to answer the question is to consider optimality principles. Starting from the seminal work by Dubins [1] in 1957, optimal control for wheeled mobile robots has attracted a lot of attention. In [2], the problem of car parking is solved by considering a sequence of shortest length paths, i.e. the so-called Reeds-and-Shepp paths [3] (Fig. 1). Shortest paths are made of two basic maneuvers: arc of a circle (on the right/left executed in the forward/backward direction) and straight line (executed in the forward/backward direction). However, not all arbitrary concatenations of these two basic maneuvers generate optimal paths. Only some of them may be optimal. In other terms, there exists a finite family of sequences of arcs of circle and straight lines, that covers all possibilities to go from a starting configuration to any goal configuration in an optimal way. Such sequences can be seen as the *words* of a simple motion language whose alphabet is made of two letters that are *arc-of-a-circle* and *straigh-line-segment*. The car-parking motion can then be described as a sequence of words. With this perspective, motion planning is a matter of motion "writing".

This simple car-parking example perfectly illustrates the challenge of robot motion planning and control. The question constitutes the essence of robotics: how to transform an action expressed in the physical space (i.e. "park the car" or "pick up the ball on the floor") in terms of a sequence of motions that originate in the motor control space (i.e. "turn left forward, go straight, turn right backward" or "bend the legs and then move the right/left hand toward the ball")? The segmentation of complex movements is a fundamental step in order to make easier robot programming.

Paolo Salaris is with the Institut National de Recherche en Informatique et en Automatique (INRIA) Sophia Antipolis – Méditerranée, 2004 route des Lucioles, 06902 Sophia Antipolis, France paolo.salaris@inria.fr. Naoko Abe is with the Fondation France-Japon de l'EHESS, 190 Avenue de France, 75013 Paris, France naoko.abe@ehess.fr. Jean-Paul Laumond is with LAAS-CNRS, 7 avenue du colonel Roche, 31077, Toulouse, France jpl@laas.fr

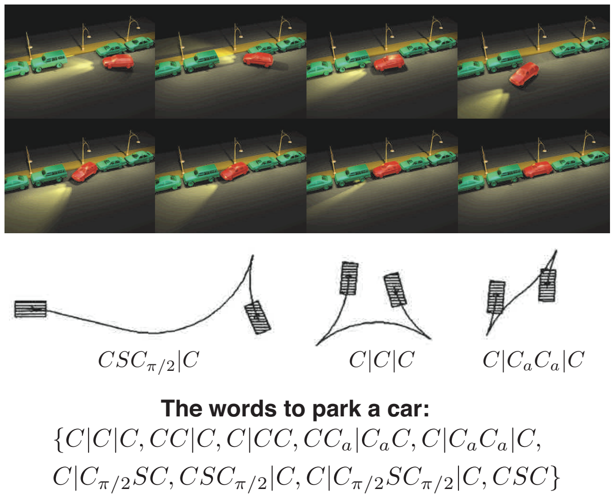


Fig. 1. The algorithm in [2] computes collision-free motions for a car-like robot. The solution to park the car is a sequence of Reeds-and-Shepp elementary paths. Each elementary path is a combination of arcs of a circle *C* and straight line segments *S*. The motion can then be "written" as a sentence from a vocabulary of nine words made of two letters *C* and *S*.

Human beings and humanoid robots share a common anthropomorphic shape. If the ultimate goal of roboticists is to provide humanoid robots with autonomy, a quest for dancers and choreographers is to understand the foundations of human movements. In spite of completely different cultures and backgrounds both communities pursue converging objectives. In this context, it is natural to assess the potential of dance notations for decomposing complex robot actions into sequences of elementary motions. Indeed, the main purpose of dance notations is to store choreographic works and knowledge of dance techniques by translating movements into specific ways as abstract symbols, letters, abbreviations, musical notations, stick figures, etc. In western culture, there are almost 90 dance notation systems, from the first appearance in 15th century to the present. Among the most popular ones, we find the Kinetography Laban, the Benesh Movement Notation system and the Eshkol-Wachman Movement Notation system [4].

The objective of the paper is to report a pluridisciplinary research tending to mirror dance notations and robot programming concepts.

B. *Scope of the paper*

The paper focuses on the Kinetography Laban. This notation system aims at scoring all anthropomorphic motions independently of any behavior or any action and hence can be exploited also with humanoid robots.

The first objective of this paper is to disseminate in the robotics community the Kinetography Laban as a way to segment and analyse complex movements of humanoid robots. Doing so, the second objective is to lay the foundation for a more ambitious goal of simplifying robot programming by means of motion segmentation. In particular we will see how the respective notions of robot action and robot motion (e.g. [5]) can be expressed within a *same* notation system. Our study is supported by two main experiences. The first one is related to the execution of an action: "picking up a ball". We point out how the Kinetography Laban may score the task at different levels of detail according to the objective to be reached, e.g. action execution or gesture imitation. It can range from a simple notation of a complex action to a detailed description of a simple motion. This makes the Kinetography Laban an useful tool that allows e.g. to capture the motion differences in executing the same action and hence gives a measure of naturalness of the whole action. In our opinion, a single quantifying criterion, which should be chosen among the several ones available in the literature, would not reach the same objective. However, we will also show that Kinetography Laban might be useless in spotting the differences between two movements without the context. This is due to the fact that Kinetography Laban operate in the physical space while the main differences between two movements might be in the motor control space. The second experience accounts for a dance imitation also reported in [6]. The dance score is translated in terms of a robot program, i.e. the so-called Stack of Task (SoT) [5]. Even if the dance movements are simple and not challenging for a humanoid robot, significant differences appear between the original movements and the robot ones. Such differences are enlighten by comparing the Kinetography Laban scores that describe the human and humanoid robot motions. They ask for a better understanding of what makes a movement natural.

The structure of the paper is as follows. We first review researches related to the segmentation of complex movements, the dancing robots and the computational scoring. Then, Section II introduces the basics of the Kinetography Laban. Section III refers on the first experience of picking up a ball. The motion performed by the HRP-2 robot to pick up the ball is notated via the Kinetography Laban. The objective is to point out the flexibility and the limitations of this notation system in expressing anthropomorphic movements with different levels of details. In section IV, we summarise the experience reported in [6] of translating the Laban score of a particular dance, a.k.a. "Tutting Dance" into a hierarchical sequence of tasks to be executed by the humanoid robot Romeo. The Kinetography Laban is used to compare Romeo's movements with the dancer's ones. It appears that Romeo's movements differ from the human ones. We will see how these differences might refer to recent neuroscience and biological studies.

C. Segmenting complex movements

Several experimental evidences promote the idea that motor actions and movements in both vertebrates and invertebrates are made of elementary building blocks [7], i.e. it is segmented and the combination of this sort of alphabet gives rise to a complex action or movement. In particular, the motion segmentation of complex human movements is widely studied and a lot of works can be found in the literature. The main objective is to find out this alphabet of human movements. For instance, in [8], authors automatically construct a directed graph called motion graph that encapsulates connections among the database from human motion capture data. Motion can be generated simply by building walks on the graph. In [9] the role of a parameter that characterises the two-thirds power law has been investigated. This parameter is approximately constant during extended parts of the movement and only shifts abruptly at certain points of the trajectory: this can be interpreted as an indicator for segmented control. Recently, in [10] authors show that imagined trajectories do follow the two-thirds power law. These findings therefore support the conclusion that the coupling between velocity and curvature originates in centrally represented motion planning. However, for particular cyclic or repetitive actions, as e.g. elliptical and figure eight patterns of different sizes and orientations performed by using the whole arm, there is no evident segmentation in the motor control space but rather continuous oscillatory patterns [11]. In the field of learning by demonstration, in [12] authors introduce a general approach for learning robotic motor skills from human demonstration. By using a non-linear differential equation to be learn in order to represent an observed movement, they build a library of movements by labelling each recorded movement according to task and context (e.g. grasping, placing and realising). In [13] a hierarchical framework that is capable of learning complex sequential tasks from human demonstrations has been proposed. Through a task segmentation and action primitive discovery algorithm, both the high-level task decomposition and low-level motion parameterisations can be achieved for each action. Finally, in [14], authors propose to use non-negative matrix factorisation to address the problem of segmenting combinations of initially unknown human motion primitives associated with ambiguous sets of linguistic labels during training. This technique allows the system to find the combinatorial structure of parallel combinations of unknown primitives.

II. Dance notations

Dance notation is to dance what musical notation is to music and what the written word is to drama. It is basically a symbolic description of human movements and forms by using graphic symbols and figures, numerical systems, path mapping, as well as letters and words. A recorded dance notation that describes through symbols a dance is known as a dance score. The most currently used dance notation systems are the Kinetography Laban (Labanotation), created and published at the first time by Rudolf Laban in the late 1920s, the Benesh Movement Notation, invented by Joan and Rudolf Benesh in the late 1940s, and the Eshkol Wachman Movement Notation, created in Israel by dance theorist Noa Eshkol and Avraham Wachman in the late 1950s. All of them allow notating every kind of human movements [15]. However, they differentiate in the way they represent the human body and its movements. We report here a brief description of Benesh and Eshkol Wachman Movement notation while we reserve a more detailed description for the Kinetography Laban in the following.

Benesh Movement Notation is very similar to the modern staff music notation. Indeed, it is recorded on a five line stave from left to right, with vertical bar lines to mark the transition of time. For this reason, Benesh notations is displayed in synchronization with a musical staff. Benesh notation draws the position of a dancer as seen from behind, from the top of the head down to the feet. From top to bottom, the five lines of the stave coincide with the head, shoulders, waist, knees and feet. The system uses abstract symbols based on figurative representations of the human body. Additional symbols are used to notate the dimension and quality of movements.

Eshkol Wachman Movement Notation scores are written on grids, where each horizontal row represents the position and movement of a single limb, and each vertical column represents a unit of time. Eshkol-Wachman movement notation deals the body as a stick figure. The body is divided at the joint level, and between two consecutive joints a line segment is defined. A spherical coordinate system is used to relate those segments in three-dimensional space. Positions of the free end of the segment can be defined by two coordinate values on the surface of that sphere. Segment positions are written somewhat like fractions, with the vertical number written over the horizontal number. The horizontal component is read first. These two numbers are enclosed in brackets to indicate whether the position in being described relative to an adjacent limb or to external reference points, such as a stage. Movements are shown as transitions between initial and end coordinates.

Kinetography Laban, or Labanotation, is a system of recording all forms of movement through graphic symbols and it is used not only by dancers to write down choreography but also in every field in which there is the need to record movements of an anthropomorphic body [16]. The Labanotation uses four factors to describe a movement: the parts of the body, the space (by using direction and level symbols), the duration, the beginning and the end of the movements.

In the Kinetography Laban, the occurrence of movement is called vertical stroke or “action stroke”. The reading direction is from the bottom and a double line denotes the beginning of the movement. As a consequence, any symbol before this double line refers to a starting configuration (see Fig. 2(a)). An action can occur on the left side or on the right side of the body. To separate action stroke that refers to one side of the body or the other, a vertical line, called center line, is drawn and connected to the double starting line.

Kinetography Laban uses a vertical three-line “staff” that represents the body (see Fig. 2(a)). The center line is the center line of the body, dividing right and left. A staff concerns the human body and his movement. Vertical columns on each side of the central line are used for the main parts of the body. As a consequence, by placing the movement indication in one of the vertical column of the staff, a movement for a particular part of the body is defined. Fig. 2(b) shows which part of the body each column refers to in a Standard Staff. Referring to Fig. 2(b), the central columns immediately next to the center line represent the support column. Symbols placed in these columns indicate progressions of the whole body through the transfer of weight. The second columns, just next to the support columns, are used to notate leg gestures, i.e. a movement of legs that does not carry weight. These columns can be used also for specific part of the legs (thigh, lower leg, feet). In the third columns, outside the three-line staff, symbols describing the gestures for the upper body, the torso and all its parts are placed. The forth columns, immediately beyond the torso columns, is for arm gestures. As for legs, also in this case, if necessary it is possible to add columns to precise the part of arm symbols refer to. Finally, the last column on the right, slightly apart from the other columns, is the head column.

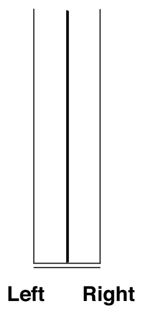
The main building blocks of the Labanotation are the direction symbols, see Fig. 2(c). These symbols define the spatial directions in which the part of the body should move in order to reach a given position. This representation of gestures suggests that, in the Labanotation, the final destination is more important than the followed path. It is important to note that the Kinetography Laban is a movement notation system. Indeed, symbols represent changes in the current body configuration produced by a movement. As a consequence, there are not symbols dedicated to represent an absence of movements.

The directions in space are specified with respect to a central point, which is called *place* and represented by a rectangle (see Fig. 2(c)). By slightly changing this symbol, 9 main directions can be also specified w.r.t. the central point. Moreover, by using 3 different shading, 3 different levels (low, middle, high) can be also specified (see Fig. 2(c)). The combination of the 9 main direction symbols with the 3 shading levels give rise to 27 principal directions. Notice that, the direction symbols state only information about the direction and level to be reached. Once these symbols are placed in a column of the vertical staff it is possible to know which part of the body the symbols refer to and hence the direction and level to be reached w.r.t. the point of attachment of that body part. For example, the whole arm is attached to the body by the shoulder. The shoulder is the point from which all directions and levels radiate. The whole arm can move with respect to the shoulder in order to reach with the extremity, i.e. the hand, the direction and level state by the symbol. The hand is considered in this case the free-end point of the arm.

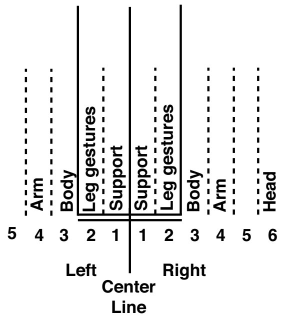
The length of the direction symbol indicates duration of movements, see Fig. 2(d). The longer the symbol is, the slower the movement will be. Of course, the beginning of the symbol indicate the beginning of the movement and the end of the symbol indicates the end of the movement.

To describe other details about the movement executions, specify parts of the body as finger, palm or back of the hand or parts of the body that have to get in touch with others or with the environment, particular signs can be used. For an exhaustive description of all these symbols and signs, we refer the reader to [16].

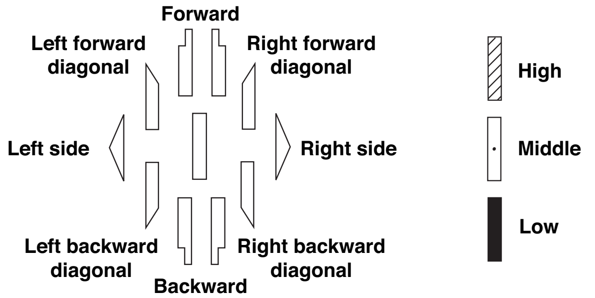
We consider the Kinetography Laban in our experience for three main reasons: its geometric representation of the space around the human body, its more intuitive symbols than other dance notation systems to describe movements and its simplicity in writing/reading simple scores. These peculiarities, for very simple movements as the ones considered in this paper, make easier the process of translating and automatising a score in a robot programming for humanoid robots even for a non expert notator.



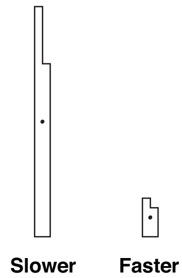
(a) The three-line staff represents the body.



(b) Standard staff with column gestures of the body parts and support of the weight.

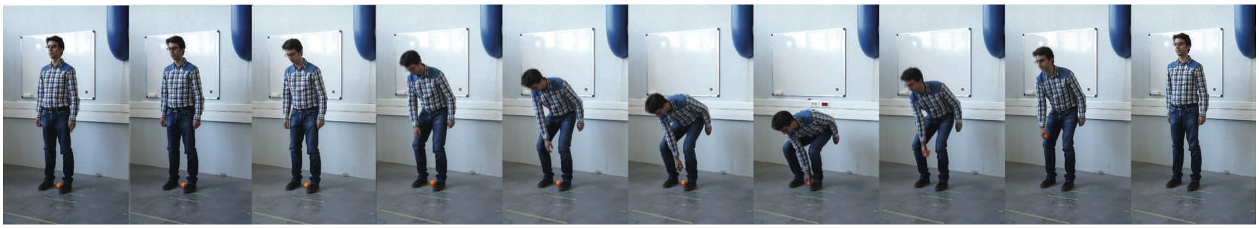


(c) Direction symbols and levels to specify the spatial directions and level in which the part of the body moves to reach a given position.



(d) Length of symbols means duration.

Fig. 2. The main elements to write down a movement by using the Kinetography Laban: the three-line staff with columns for gestures in (a) and (b), the direction symbols and levels (c), and the duration of a movement specified by the length of the symbol (d)



(a) Paolo picks up the ball between his feet. He can do it without changing his feet positions.

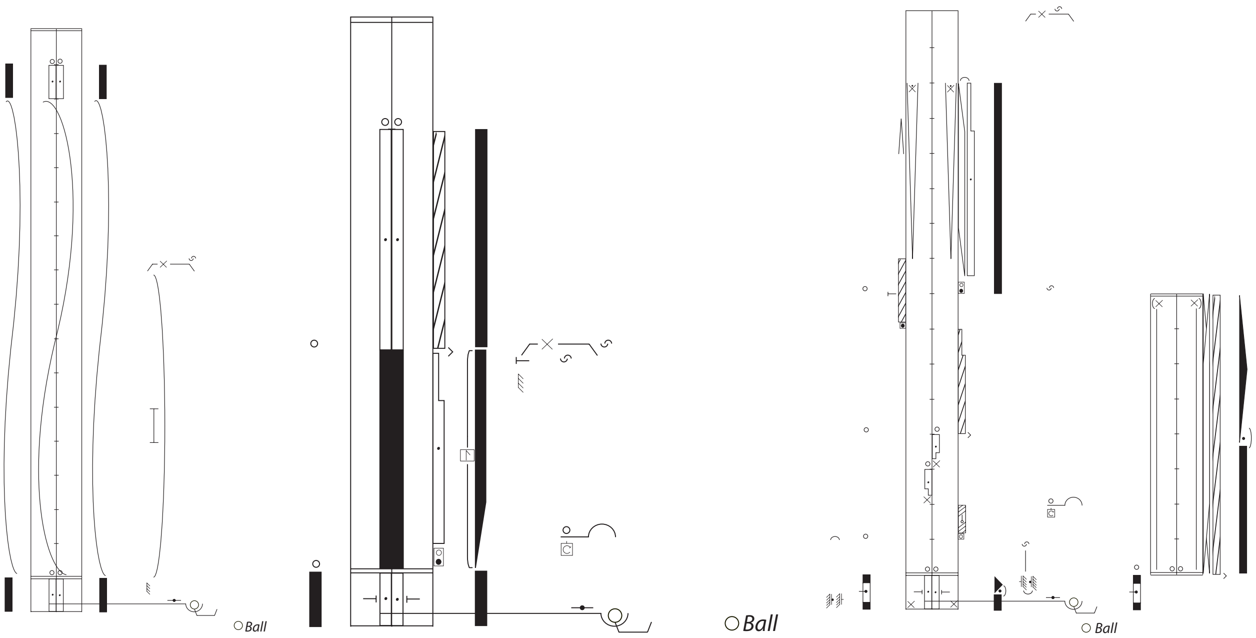
(b) HRP-2 picks up the ball between its feet. "stepping away" is a direct consequence of the action "pick up the ball". Indeed, there is no dedicated module in charge of stepping away but it is part of the module "pick up the ball".

(c) Tiphaine is executing a motion by reading the notation in Fig. 4(c) which describes the movements of HRP-2 in Fig. 3(b). For Tiphaine, "picking up a ball" is not an objective: "picking up the ball" is just part of a complex motion she has to perform.

Fig. 3. To pick up the ball between its feet the robot has to step away from the ball while humans can directly grasp the ball without changing their feet positions. This is a consequence of the mechanical differences between the human body and HRP-2 body.

III. From Simple Action Notation to Detailed Motion Notation

Let us consider the simple action of grasping a ball on the floor (see Fig. 3). It gives rise to a complex motion involving the coordination of all body segments. In particular, the legs should naturally contribute to the action so that "bending knees" becomes a direct consequence of the action "pick up the ball on the floor". The action "pick up the ball" can be notated as in Fig. 4(a). The score tells us only the initial posture, i.e. standing, the arms configuration at the beginning and at the end of the action, i.e. the arms are stretched out along the body, and the initial position of the ball which is on the floor between the feet. However, it does not mention how to pick up the ball in detail. Moreover, all the symbols on the right side of the three lines staff describe that the right hand has to reach the ball by following a direct path and grasps it at a given instant. This is the only information included in the notation.



(a) Notation of the action "Take the ball" by using the Kinetography Laban.

(b) The detailed description of the movement in Fig. 3(a) by using the Kinetography Laban.

(c) The detailed description of the movement in Fig. 3(b) by using the Kinetography Laban.

Fig. 4. Different Laban scores describing the motions motivated by the action of "Take the ball". The figures may appear as obscure for readers not aware about Laban notation details. Their purpose is mainly illustrative to show that differences appear. Moreover, the presence of a symbol modeling the ball argues that the notation not only deals with the movement of the human body parts, but also with the movement of the ball.

Next subsections are dedicated to:

- describe how HRP-2can be programmed in order to pick up the ball on the floor between its feet exactly as it is described in in the Laban score of Fig. 4(a);
- show how the flexibility of the notation in describing anthropomorphic movements can be exploited to notate with different level of details, going from directly translating the sentence "pick up the ball on the floor between feet" (see Fig. 4(a)) to precisely describing the movements of all body segments (see Fig. 4(b) and Fig. 4(c)). It can be also used to enlighten the main differences between two movements originated from the same task/action score as the one in Fig. 4(a).

A. HRP-2 takes the ball on the floor

In [17] authors provide a solution to the problem of programming HRP-2 to pick up the ball on the floor that basically implements the Laban score reported in Fig. 4(a). The critical issue is to enlarge the feasible workspace of the robot arms when needed, i.e. when the object to grasp is out of the reaching space. This is done by allowing few steps. The foot placements are determined by a continuous deformation of a virtual robot motion. The virtual robot is made of the robot augmented with a virtual kinematic chain modeling the sequence of possible foot placements. Doing so, the whole-body grasping task may be solved by a classical inverse kinematics algorithm.

The final complete movement obtained by programming HRP-2 as described in [17] is shown by snapshots in Fig. 3(b). The main reason why the robot steps away from the ball before picking up it is to reach a configuration such that the self-collision can be more simply avoided during the task. Moreover, from this new position, also the balance can be more simply guaranteed. It is important to note that there is not a dedicated module in charge of "stepping away" but this is a direct consequence of "picking up the ball". In other words, the legs naturally contribute to the task.

B. On the use of the Kinetography Laban to compare movements

When we asked Paolo to pick up the ball without giving any constraints, he takes the ball without changing his feet positions (see Fig. 3(a)). He just bends his knees and his right hand grasps the ball. "Bending knees" is not explicitly expressed by the Laban score in Fig. 4(a) as well as "stepping away" before grasping the ball as HRP-2 did. The simplest Laban score that just describes the action "pick up the ball on the floor" has not enough details to describe how a movement should be executed or to compare two different movements originate from the same action/task – Paolo and HRP-2 executed the action in different ways (maybe another humanoid robot and an other human subject might execute the same action in a completely different way[1]). The main objective of the score in Fig. 4(a) is more about communicating

[1]Notice that, the study of what is the most natural movement for humans to pick up a ball on the floor is not within the scope of this paper. For our purposes, it is sufficient to observe that there are different ways to do that but, without a sufficient level of details in the Laban score, it is not possible to appreciate these differences.

Fig. 5. On the left picture, the robot has to grasp the ball on the table in front of it. As the ball is far away from the robot but reachable without moving the feet, the robots bends forward. However, to maintain balance, the left arm moves behind. In the figure on the right, the robot has to grasp a ball in front of it and a ball behind (of course the ball behind has been intentionally placed at the end position of the left hand on the left picture). Is it possible to spot the differences between these two motions by using the Kinetography Laban?.

to the reader the action or task to be executed, the movements behind the action are less important.

A same action may be written down with different levels of details accounting for the purpose of the notation including what the notator wants to transmit to the performer and who is the reader of the score. This is not a weakness of the notation system, but a strength. For instance, the score depicted in Fig. 4(b) is the detailed notation of Paolo's movement. The notation describes his manner to take the ball with many details. It includes how he reaches the floor with the hand (e.g. rotation of the torso), how he grasps the ball (e.g. the choice of the right hand), the direction of his gaze, and the motion timing. Fig. 4(c) shows a notation of the whole movement of HRP-2 robot. It includes exactly the same level of details as the score in Fig. 4(b). By comparing the two Laban scores it is possible to appreciate that these two movements are different and that the HRP-2 movement appears to be much more complex. Notice that, HRP-2 does not execute the Paolo's score because of its mechanical constraints/limits.

Finally, we asked Tiphaine, an experienced Laban notator, to read the score in Fig. 4(c) concerning the detailed motion of HRP-2 and to perform the motion only according to the score (see Fig. 3(c)): she was not aware of the objective of the study and she did not see HRP-2 before executing her motion. For Tiphaine, "picking up the ball on the floor" is not an objective, it is just part of a complex motion she has to perform. The motions executed by Paolo and Tiphaine differ. However the underlying action is exactly the same in both cases, i.e. grasping the ball. Paolo's motion reflects the intention to grasp the ball. His motion is not imposed. Tiphaine's motion reflects the imitation of a motion. In her case, grasping the ball is only a side-effect of the motion.

Concluding, previous examples show how flexible is the Kinetography Laban as a motion notation system. Indeed, according to the objective of the notator, the score may encode different levels of details ranging from a simple description of a complex action to a detailed description of a simple motion.

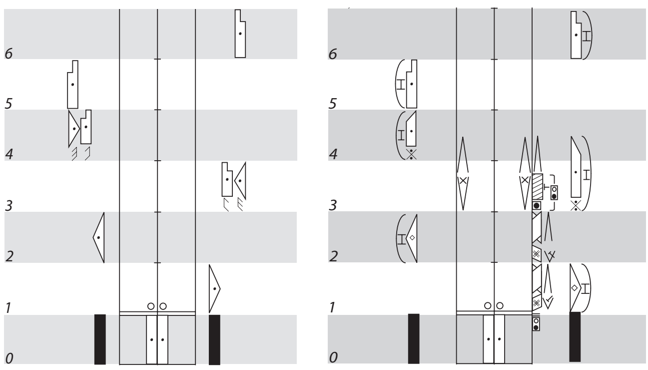
From previous experience, we can deduct that the Kinetography Laban can be used to compare humanoid's actions/movements with humans' ones. A single quantifying criterion, which should be chosen among the several ones available in the literature, would not reach the same objective. However, it is important to recall that Kinetography Laban translates a movement in symbols by looking only at the physical space. This might complicate the comparison of movements or make it impossible without a description of the context. In some cases, the comparison might be more simple in the motor control space. Let us consider, for example, the two scenarios reported in Fig. 5 taken from [18]. In the first scenario, the humanoid robot has been programmed to reach with the right hand the ball on the table in front of it. However, as a secondary effect of the main task that consists in maintaining robot balance, the left hand moves behind the robot. In the second scenario, the robot not only has to grasp the ball on the table in front of it but it has also to grasp a second ball behind (of course the ball behind has been intentionally placed at the end position the left hand reaches in previous experience). By looking at the two movements of the robot, it is not possible to spot the differences. Only the context, basically the presence of one instead of two balls to be grasped, gives us some hints about the intention of the action/movement. The Kinetography Laban describes an action/movement as it looks like to the notator's eyes. However, depending on the level of details, the two movements can or cannot be differently notated. Let us assume that a low level of details is used, basically similar to the one in the score of Fig. 4(a) which describes the action of "picking up a ball on the floor". It is straightforward that, in the first scenario, the movement of the left arm will not be notated. Indeed, the main action to write down is to grasp the ball on the table. In the second scenario, both actions are written down. If a high level of details is used, the movements of all parts of the humanoid robot will be notated and, as they appear very similar, the only difference will be the presence of two balls in the second scenario and only one ball in the first scenario. By using a high level of details, the actions of grasping the balls are only part of a complex movement. However, results in [18] show that the movements of the two scenarios can be distinguished in the proper task space. The presented method takes advantage of the knowledge of what task the robot is able to do and how the motion is generated from this set of known controllers, to perform a reverse engineering of an observed motion. The method is based on the projection operation into the null space of a task to decouple the controllers. In other words, in [18] authors access to the motor control space to distinguish similar looking movements that is exactly what Kinetography Laban, which is designed to describe human's movements, is not able to do.

In the next section, after summarising the experience reported in [6] on how to bridge the gap between motion notation and robot programming systems, we describe the main differences between humans and Romeo movements.

IV. On the naturalness of movements: the "implicit rules" of the Kinetography Laban

In [6], a simple Laban score of the Tutting Dance sequence, i.e. a dance that mainly concerns the arms and the hands movements, has been described by using the Kinetography Laban and translated in robot motion. The method is based on the Stack of Tasks (SoT), a robot programming system introduced in [19]. The 27 principal direction symbols used to describe the Tutting Dance (c.f. to [6] for details) are the starting point to translate the Laban score in the SoT. In other words, depending on the current configuration of humanoid robot Romeo, each principal direction symbol is translated as a task in the operational space. Indeed, each direction symbols specifies the main directions and levels w.r.t. the point of attachment of the body part which the symbol refers to (cf. Fig. 2(c)). As a consequence, w.r.t. the point of attachment, to each symbol it is possible to associate a homogeneous transformation matrix that specifies both the position and orientation of a reference frame at that direction and level. Based on the current position of the body part and the desired one specified by one of the principal direction symbol, a task function is defined as the error in terms of both rotation and translation between the current position in space of the reference frame attached to the free-end and the desired one. The SoT software [20] is then used to determine suitable control signals for the motor of the robot such that the error becomes zero, while guaranteeing at the same time other tasks (e.g. maintain static equilibrium, maintain the part of the body that are not involved by movement fixed and so on). A dynamic hierarchy of tasks is indeed obtained.

Once the whole movement is translated in the SoT, suitable control signals are sent to the motor of a simulated version of the humanoid robot Romeo and the whole movement has been reproduced by the robot. One of the main difference between



(a) Laban score for a dancer (b) Laban score for Romeo

Fig. 6. A comparison between the Laban score of the first part of the Tutting Dance executed by a dancer and Romeo. The main difference is about the path of the free-end of the arm (here considered to be the wrist). The path of Romeo is along a straight line between the initial position to the final one (see Fig. 7). There are also several movements of the torso. Moreover, the arm are a little curved during the movement and the gesture are slightly overlapped (the movement in the original score is a "staccato" movement).

Romeo and human movements from the Kinetography Laban perspective (i.e. in terms of symbols and signs in the Laban score) is the arc with the letter "I" (capital i) to the side of each direction symbol inside the arm columns (c.f. to [6] for details about other differences). This new sign basically indicate a description of the path that the free end of the arm is now executing, i.e. a straight line. In the context of the Kinetography Laban, the addition of this sign to the side of each direction symbol constraints the movements of the free-end of the part of the body the symbol refers to along a straight line. Without that sign, the movement obeys to the implicit rules of the Kinetography Laban that, after several years of analysis, reflect the natural way of moving.

The direction symbols indeed state only information concerning the element of direction. Once they are placed in the appropriate column of the vertical staff, it is possible to determine which part of the body has to move. Moreover,

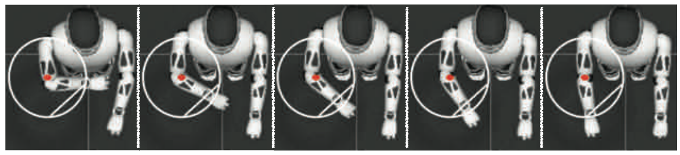


Fig. 7. A sequence of snapshots for the movement at step 6 in the Laban score of Fig. 6(a). The free end of the right arm moves along a straight line between the starting position and the desired one. This gives rise to other undesired and unnatural movements. In this case, the elbow (red point) does not remain at a fixed position in space.

depending on the current configuration of the body, also information about the path that the free-end of the body part the symbol refers to can be obtained, giving rise to the so called "implicit rules".

The information about the movement execution is achieved from the concept of *degree-distance* between direction symbols. Each symbol basically indicates a point to be reached around the point of attachment of the body part to the rest of the body (e.g. the shoulder for the arm). Symbols that correspond to adjacent points in space are at a *first–degree distance* from one another (see Fig. 8). For example, if the arm moves from forward middle to the adjacent right front diagonal point, this is a first-degree distance. In this case, the free end of the arm, i.e. the hand, describes an arc of circle on the surface of the sphere whose centre is the shoulder. This is a so called *peripheral movement* in Laban system. All movements between first–degree distance points produce this type of path. If the arm moves from forward

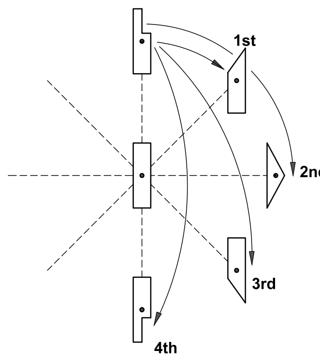


Fig. 8. Degree of distance between direction symbols. According to this distance, the free-end of the arm has to generate a *peripheral movement*, a *transversal movement* or a *central movement*.

middle to side (right or left) middle, points are at *second–degree distance* (see Fig. 8) and the hand describes a quarter of circle w.r.t. the shoulder. Also in this case we obtain a peripheral movement. All movements between second–degree points are performed without any special flexion of the arm unless otherwise specified with the addition of particular signs.

If two points are at *third–degree distance*, the hand moves along a trajectory closed to the body. Hence it is not a peripheral path. Indeed, the arm is slightly bent and the free end of the arm takes a path between periphery and centre ("*in place*"). This is called *intermediate situation or transversal movement*.

Finally, diametrically opposite points are at *fourth–degree* *distance*. For example this is the case when the arm moves from forward middle to the extreme opposite direction, i.e. backward middle. The arm comes back "*in place*" then extends again to outside. These type of movements are called *central movement* in Kinetography Laban.

The control laws used to move the arms of Romeo do not generate all this variety of movements. Indeed, the control law implemented in Romeo simply reduce the distance between the current configuration of the free-end of a body part and the desired one. The resulting path for the free-end of a body part is a straight line, with noticeable loss in naturalness. Indeed, to generate a straight line path, other undesirable and unnatural body movements are necessary. To avoid this movements, an ad-doc control law that moves the free-end of a body part along peripheral, central, or transversal movement might be determined. However, the implicit rules of the notation come from several years of observations and they are based on the naturalness of human movements, also induced by the mechanical structure of the body. As often conjectured in robotics, an optimality principle might underline human movements [5]. It would be hence interesting to understand what is this principle, to express it in a suitable mathematic manner and than to use it to determine the suitable control laws for humanoid robots.

One of the main limitation in translating the Laban score in humanoid robots is then to obtain movements that resemble the human ones. Several biological studies try to find the principles that explain, among all possible movements, the ones humans perform in everyday tasks [21]. In [22], a robotic approach for the synthesis of human motion using a task-space framework is presented. In this framework, authors showed that task-driven human motions come from the use of physiomechanical advantage of the human musculoskeletal system under physiological constraints. Regarding arm movements only, in [23] a study of the coordination of voluntary human arm movements is presented. Authors defined an objective function as a measure of performance for any possible planar multi-joint arm movement. By using dynamic optimisation theory, they showed that the objective function is the square of the magnitude of jerk of the hand integrated over the whole movement. As a consequence, the main objective of motor coordination is to reproduce the smoothest movement of the hand. However, if arms move on a vertical plane or in general not only on a horizontal one, the force of gravity plays an important role. To move against gravity strongly differs from moving along the gravity vector. In [24], authors tried to understand how the central nervous system plans and controls vertical arm movements. By using the optimal control theory, it has been shown that the experimental findings can be explained in terms of the minimisation of an optimal motor planning (minimum absolute work-jerk) that integrates the direction and the magnitude of gravity torque and minimises the absolute work of forces (energy-related cost) around each joint.

Another critical question in motor control is how the central nervous system deals with redundancy. One way to simplify the motor control is to combine several degrees of freedom into synergies. In [25], by principal component analysis authors showed this behavior during fast, unrestrained, and untrained catching movement. This provides a reduction of the high dimensional motor space into a few dimensional control space, giving rise to a simplification in the optimisation procedure.

Concluding, retargeting a human movement in a humanoid robot is a known challenge. Kinetography Laban score can be used to simplify the robot programming phase. However, the following two main issues should be taken into account:

- Human body and humanoid robot body differ. Paolo and HRP-2 pick up the ball on the floor between the feet in different manners. The main reason is that the body of HRP-2 does not allow to move its hand between its feet while avoiding self-collision. It is hence forced to step away and reach a more comfortable configuration. Moreover, to program HRP-2 in order to pick up the ball on the floor, we may benefit from the score in Fig. 4(a) but not from the other score. Indeed, the score in Fig. 4(c) does not take into account the mechanical limits of HRP-2, while the second score in Fig. 4(b) is too detailed and hence complex to be programmed. The level of details adopted in the Laban score is then a critical issue. Moreover, human motion notations are all based on the kinematic structure of the human body. Adapting the notation to another structure is certainly possible, but it is a challenge by itself.
- The question of the naturalness of a movement. In Kinetography Laban, the rules to move the hand in a given direction have been defined and described on the basis of a long experience in observing human movements. However, there are not a priori interested by causality principles, i.e. by the origin of the movement. The origin of the movement takes place in the muscle control space. However, it is not necessary to tell a dancer what muscles he/she has to activate to perform a desired movement. Muscle activation is an unconscious process. With the fundamental problem of inverting actions expressed in the physical space into motor controls, roboticist have to face the causality principle. This is why, like neurophysiologists, roboticists try to exhibit general movement laws to explore plausible causality principles. Combining the minimisation of suitable objective functions, extracted from human's movement analysis, and the concept of synergies to reduce the variables to be optimised might be an interesting manner to fill the gap between dance notation with their rules of naturalness and robot programming.

V. CONCLUSIONS

It is important to stress that the objective of this paper was not to propose a new programming system for humanoid robots. The main objective was instead to disseminate in the robotics community the Kinetography Laban as a way to segment and analyse complex movements of humanoid robots. In particular, we have shown how the respective notions of robot action and robot motion can be expressed within a same notation system and how the Kinetography Laban can be used to compare human and robot movements. Moreover, we have also shown how the Stack of Task can be used to translate a dance score in robot motions. By comparing the Kinetography Laban scores that describe the human and humanoid robot motions, new perspectives about what makes a movement natural by considering the implicit rules of the Kinetography Laban have been also drawn.

We have seen that dance notation and robot programming pursue two different goals in two different spaces. Dance notators mainly address the physical space, while roboticists tend to bridge both physical and motor spaces. In spite of these differences of objectives, the various experiences presented in this paper contribute to open a pluridisciplinary research perspective based on a mutual understanding between robotics and movement science as addressed by choreographers and dancers. In particular the relationship between action and motion, as well as their symbolical and computational foundations, are complementary developed by dance notation practitioners and roboticists. The dialogue deserves to be deeper explored.

Acknowledgment

This work is supported by ERC Advanced Grant 340050 Actanthrope. Authors thank Noëlle Simonet, professor of Kinetography Laban at the "Conservatoire National de Musique et de Danse" in Paris, for reviewing the Laban scores, and Tiphaine Jahier, dancer and Laban notator, for her participation to read notations and perform actions.

References

[1] L. E. Dubins, "On curves of minimal length with a constraint on average curvature, and with prescribed initial and terminal positions and tangents," *American Journal of Mathematics*, vol. 79, no. 3, pp. pp. 497–516, 1957.

[2] J.-P. Laumond, P. Jacobs, M. Taix, and R. Murray, "A motion planner for nonholonomic mobile robots," *IEEE Transactions on Robotics and Automation*, vol. 10, no. 5, pp. 577–593, Oct 1994.

[3] J. Reeds and L. Shepp, "Optimal paths for a car that goes both forwards and backwards," *Pacific journal of mathematics*, vol. 145, no. 2, pp. 367–393, 1990.

[4] A. Hutchinson Guest, *Choreo-Graphics, A comparison of Dance Notation Systems From the Fifteenth Century to the Present*. New York: Gordon and Breach Science Publishers S.A., 1989.

[5] J.-P. Laumond, N. Mansard, and J. B. Lasserre, "Optimization as motion selection principle in robot action," *Communications of the ACM*, vol. 58, no. 5, pp. 64–74, 2015.

[6] P. Salaris, N. Abe, and J.-P. Laumond, "A worked-out experience in programming humanoid robots via the kinetography laban," in *Dance Notations and Robot Motion*, J.-P. Laumond and N. Abe, Eds. Cham: Springer Tracts in Advanced Robotics (111), 2016, pp. 339–359.

[7] T. Flash and B. Hochner, "Motor primitives in vertebrates and invertebrates," *Current Opinion in Neurobiology*, vol. 15, no. 6, pp. 660 – 666, 2005, motor systems / Neurobiology of behaviour.

[8] L. Kovar, M. Gleicher, and F. Pighin, "Motion graphs," in *Proceedings of the 29th Annual Conference on Computer Graphics and Interactive Techniques*, ser. SIGGRAPH '02. New York, NY, USA: ACM, 2002, pp. 473–482.

[9] P. Viviani and M. Cenzato, "Segmentation and coupling in complex movements." *Journal of experimental psychology: Human perception and performance*, vol. 11, no. 6, p. 828, 1985.

[10] M. Karklinsky and T. Flash, "Timing of continuous motor imagery: the two-thirds power law originates in trajectory planning," *Journal of Neurophysiology*, vol. 113, no. 7, pp. 2490–2499, 2015.

[11] D. Sternad and S. Schaal, "Segmentation of endpoint trajectories does not imply segmented control," *Experimental Brain Research*, vol. 124, no. 1, pp. 118–136, 1999.

[12] P. Pastor, H. Hoffmann, T. Asfour, and S. Schaal, "Learning and generalization of motor skills by learning from demonstration," in *IEEE International Conference on Robotics and Automation (ICRA)*, May 2009, pp. 763–768.

[13] N. Figueroa, A. L. Pais, and A. Billard, "Learning complex sequential tasks from demonstration: A pizza dough rolling case study," in *Proceedings of the 2016 ACM/IEEE International Conference on Human-robot Interaction (HRI)*. ACM, 2016.

[14] O. Mangin and P. Y. Oudeyer, "Learning to recognize parallel combinations of human motion primitives with linguistic descriptions using non-negative matrix factorization," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct 2012, pp. 3268–3275.

[15] J. Challet-Haas, "The problem of recording human motion," in *Dance Notations and Robot Motion*, J.-P. Laumond and N. Abe, Eds. Cham: Springer Tracts in Advanced Robotics (111), 2016, pp. 69–89.

[16] A. H. Guest, *Labanotation: the system of analyzing and recording movement*. Psychology Press, 2005.

[17] O. Kanoun, J.-P. Laumond, and E. Yoshida, "Planning foot placements for a humanoid robot: A problem of inverse kinematics," *International Journal of Robotics and Research*, vol. 30, no. 4, pp. 476–485, Apr. 2011.

[18] S. Hak, N. Mansard, O. Stasse, and J. P. Laumond, "Reverse control for humanoid robot task recognition," *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, vol. 42, no. 6, pp. 1524–1537, Dec 2012.

[19] N. Mansard and F. Chaumette, "Task sequencing for high-level sensor-based control," *IEEE Transactions on Robotics*, vol. 23, no. 1, pp. 60–72, Feb 2007.

[20] N. Mansard, O. Stasse, P. Evrard, and A. Kheddar, "A versatile generalized inverted kinematics implementation for collaborative working humanoid robots: The stack of tasks," in *International Conference on Advanced Robotics (ICAR)*. IEEE, 2009, pp. 1–6.

[21] E. Demircan, D. Kulic, D. Oetomo, and M. Hayashibe, "Human movement understanding [tc spotlight]," *IEEE Robotics Automation Magazine*, vol. 22, no. 3, pp. 22–24, Sept 2015.

[22] O. Khatib, E. Demircan, V. D. Sapio, L. Sentis, T. Besier, and S. Delp, "Robotics-based synthesis of human motion," *Journal of Physiology Paris*, vol. 103, no. 3–5, pp. 211–219, Aug. 2009.

[23] T. Flash and N. Hogan, "The Coordination of Arm Movements - an Experimentally Confirmed Mathematical-Model," *Journal of Neuroscience*, vol. 5, no. 7, pp. 1688–1703, 1985.

[24] J. Gaveau, B. Berret, L. Demougeot, L. Fadiga, T. Pozzo, and C. Papaxanthis, "Energy-related optimal control accounts for gravitational load: comparing shoulder, elbow, and wrist rotations," *Journal of Neurophysiology*, vol. 111, no. 1, pp. 4–16, Jan. 2014.

[25] T. Bockemühl, N. F. Troje, and V. Dürr, "Inter-joint coupling and joint angle synergies of human catching movements," *Human Movement Science*, vol. 29, no. 1, pp. 73–93, 2010.