From Dance Movement to Architectural Form

by

Dimitra Stathopoulou

Supervised by

Prof. Paul Richens

Dr. Paul Shepherd

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University of Bath

Department of Architecture and Civil Engineering

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ABSTRACT

Architecture and dance, two apparently diverse subjects, are explored, analysed and interrelated in this research, through parametric modelling. The thesis is divided into five basic chapters. Firstly, the prior research regarding architecture and dance is examined, which also justifies the innovation of the current research. Secondly, the visualisation techniques that have been used so far are explored in order to record, file, compose, animate, transform or combine dance movements. Afterwards, how dance movement can be expressed and transformed within the frame of parametric modelling is explained. The tools created are then applied in two case-studies, and transformed according to the functional and spatial restrictions of each project. Finally, the outcomes of this research are summarised indicating the achievements and the difficulties of the whole process, while recommendations for further research are suggested.

Keywords

Architecture, dance visualisation, Labanotation, motion capture, parametric modelling, grasshopper, digital fabrication, playscape, skatepark.

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1. INTRODUCTION | ARCHITECTURE AND DANCE

Architecture and **dance**, despite being two apparently diverse subjects, present a complementary relationship regarding space and movement. As Peponis (1997) has pointed out, dance performs patterns of movement and creates ephemeral forms in space, while architecture, by its material substance, restricts the possibilities of movement.

Moreover, according to Mattingly (1999) both dance and architecture are forms of visual art that share a common ground, that of three-dimensional space. Thus, the vocabulary, the principles and the design processes used in both disciplines are closely related. For instance, both art forms are subject to expression, are restricted by gravity, and defined by an underlying structure.

Despite the fact that dance has inspired a lot of architects and artists, when starting research on the relationship between dance and architecture, it becomes clear from the beginning that this subject has not been sufficiently explored (Spier 2005). The available sources mainly focus on traditional theories about body and space or research on performance facilities (Spier 2005). Others examine space syntax theories and matters of perception of dance by the viewer (Gavrilou 2003). Sufficient information can also be found about the relation of a moving person within the built environment, including issues of circulation inside a building or public space and the flow of people.

The difficulty in relating movement with architecture in a direct way arose because movement is an action, and as such it is closely related to time and space. On the other hand architecture is traditionally opposed to temporality that is inherent into movement and dance.

Yet the significant progress in computational technology brought increasingly into focus the conflict between static form and motion. The emerging design tools allowed architects to explore other aspects of motion and space. The representation of architecture through animation, dynamic geometries or the use of techniques such as keyframing (Fig.1) for the generation of form, are indicative examples (Schodek 2008). Another view to movement and architecture is the literal interpretation of this subject through kinetic architecture (Harris 2002).

Nevertheless, the connection with dance has not been indicated by any of the previously mentioned approaches.

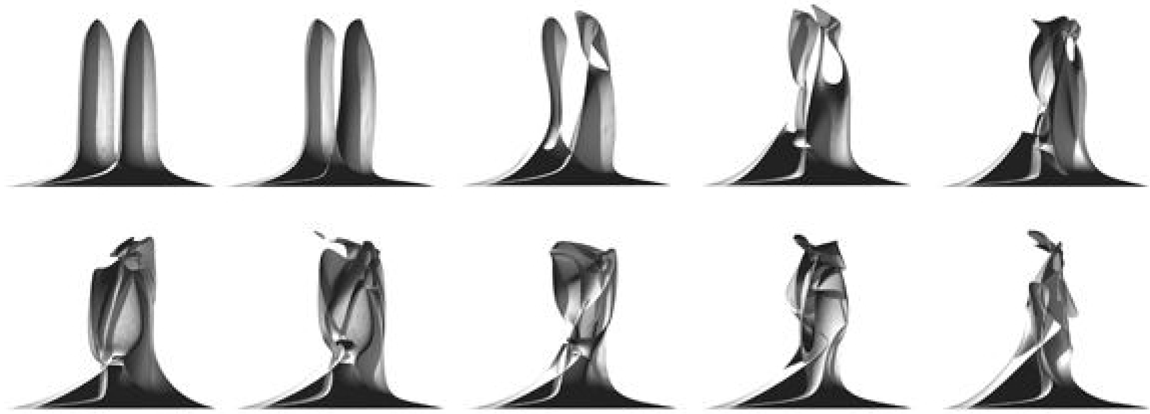


Fig. 1 Use of keyframing for the design entry for the World Trade Centre, 2002. (Architects: Ocean North)

In terms of visualisation of dance there is also lack of theoretical research. The available sources involve methodologies to extract information about dance from pictures (paintings, sketches, crafts) (Seebass 1991) or visualising choreographical data with the use of animation and computational technologies (Calvert et al. 2005). There have been various creative approaches to visualise dance in disciplines such as painting, sculpture, photography, video art, etc. Therefore, architecture presents lack of sources regarding the generation of architectural forms from dance movement.

In order to approach this subject a research methodology has been followed that starts with the analysis of dance movement to reach the association of it with geometry and architecture. More specifically, the first chapter of the thesis explores the means that have been used so far for the visualisation of dance. Starting with dance notation, and the analysis of movement, interest shifts to animation and inverse kinematics, video, William Forsythe's mixed media and eventually to Motion Capture Data. The latter formed the basis for experimentation with movement.

Firstly, the possibility of importing Motion Capture Data within design software (Rhino/Grasshopper) has been examined. After having achieved that, different kinds of motions were collected from a MoCap database for exploration and experimentation. The results were a series of diagrams, included as the appendices of the thesis, which demonstrate different ways of visualising movement.

The diagrams of dance movement indicate the necessity to create some transformation definitions in order to make the geometry applicable to the case-study. The subject of the case-study is a playscape which includes climbers generated by dance movement and a skate-bowl formed as the negative space of dance.

For the selection and classification of movements, as well as for the organisation of the parametric definitions, some of the principles of choreography and the analysis of movement have been taken into consideration, in order to provide a backbone for the creation of form through dance.

2. DANCE VISUALISATION

Dance consists of two very basic qualities; its form and its temporality. The former is possible to visualise with the use of traditional means (painting, sculpture, photography, etc.), whilst the latter requires different approaches. Ice dancing in western culture and snake dances of the Manipuri (Northeast India) are two cases where dance has inherently a visual aspect and more precisely leaves its traces in space (Seebass 1991). However, this does not apply in live dance performances where the form and shape of dance is absolutely ephemeral.

In the following chapter various techniques to record and visualise dance are presented, as well as the advantages and disadvantages of each one, and how some of those formed the basis upon which the parametric model was built.

2.1 Dance Notation and Analysis of Movement

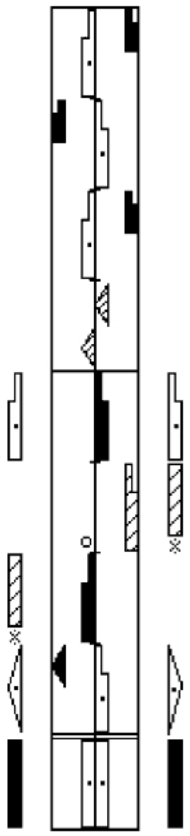


Fig. 2 Example of Labanotation stave.

Notation is used as a visualisation tool to communicate ideas in various disciplines. An example coming from everyday experience is writing. *'Writing represents speech with a sequence of letters'* (Misi 2007). Accordingly, music is notated by using notes on a stave. Like music and speech, dance has also a system to be recorded on paper. As described by Yolande Harris, in her research about architecture, music and dance:

'Notation is an interface that lies between all forms of the realisation of ideas into objects - whether architectural, musical, visual or linguistic.' (Harris 2002)

The most commonly used systems, nowadays, for notating dance are the Benesh notation and Labanotation. The creators of the former were mainly involved with classical ballet; hence Benesh notation meets well the needs of a strictly structured and disciplined movement such as ballet movement. Labanotation was formed by one of the pioneers of contemporary dance (Rudolf Von Laban); therefore this system had to be flexible enough to respond to the experimental character of contemporary dance. Both systems though, analyse human movement in terms of spatiality, time and dynamics. The system chosen to study in this research is

Labanotation, because it is considered more extensive and precise than Benesh notation, although it is more difficult to use (Williams 2008).

In 1928, Rudolf Von Laban developed a notational system with which one can record any body movement by capturing positional information for various body parts, presignifying keyframe animation systems (Wilke et al. 2005). The movement is recorded in a three-line stave that is read from the bottom to the top of the page and it is divided into measures (Fig. 2). The symbols that are placed on the same line on the stave represent movements that are occurring simultaneously. The symbols on the stave are organised at the left and the right side of the centreline, representing the left and right limbs accordingly, as well as the spine (Fig. 3). The basic symbols describe the direction, the turns, the level of movement, and its duration in time (Figs. 4 & 5). Ancillary symbols indicate the path of movement, the arrangements of dancers on the stage, the dynamics of movement and other details (Fig. 6).

BASIC SYMBOLS OF LABANOTATION

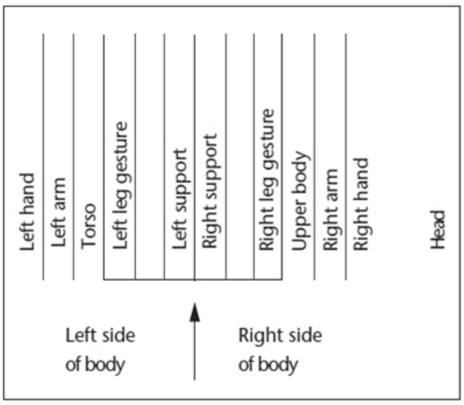


Fig. 3 The stave.

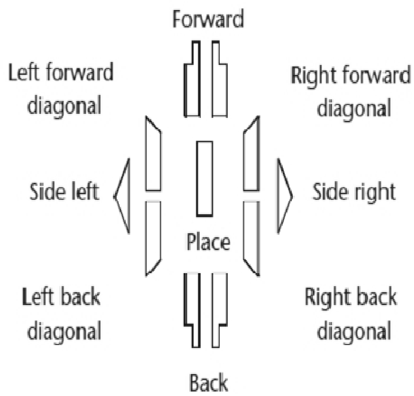


Fig. 4 Direction symbols.

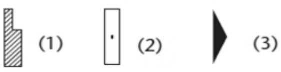


Fig. 5 Direction and level (shading) symbols: (1) forward high, (2) place middle, (3) right side low.

Fig. 6 Symbols indicating body parts: (1) head, (2) face, (3) hands, (4) front of left shoulder.

According to Laban, the different positions of the body are included within a virtual icosahedron, which he called kinesphere (Hutchinson 1970). Kinesphere is defined as the space surrounding a dancer's body and that they can potentially reach (Figs. 7 & 8). More precisely, the kinesphere is defined by a stable, vertical axis around the centre of which 27 points are marked. Consequently, as the body moves, the axis tilts and rotates, moving the kinesphere with it.

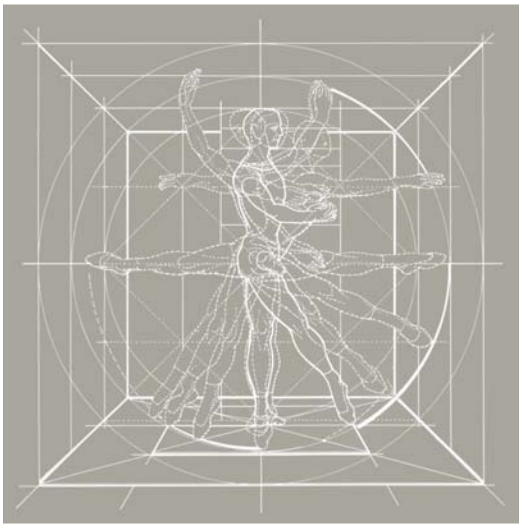


Fig. 7 Kinesphere: the area where the body is moving within.

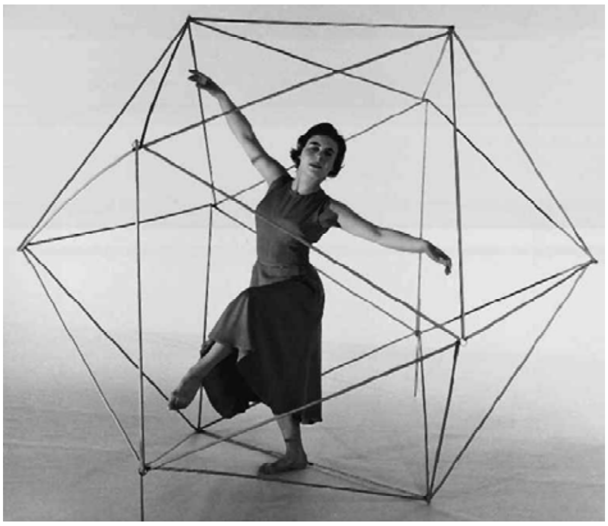


Fig. 8 The icosahedron within which Laban defined the structure of movement.

The movement can be analylised into various features (Fig. 9). These include the number of dancers, the parts of the body used, the space occupied by the body and the space around it, as well as the parameter of **time**, the **dynamics** of movement and others **spatial qualities**. The parameter of time affects the speed and the duration of movement, and as a result the rhythm. The dynamics of movement is a term used by Laban to describe the result of energy used in time. Depending on the intensity of the energy and the relation of it with time, a movement could be strong, gentle or sudden, sharp, staccato and so on. Also, Laban defined a range of movement qualities that he called efforts, combining space, time and energy (examples of efforts: punch, float, flick, dab, press, glide, slash, wring, etc.) (Rickett 1996). Other spatial qualities refer to modifications of the direction, level, and size of movement, the way that transitions take place, the degree of distance or rotation and the kinds of movement paths (Hutchinson 1970).

Labanotation succeeds in describing movement in a very explicit way. Thus, it can be applied in different disciplines and for a wide variety of purposes. Mainly, it is used in dance as a means for the preservation of choreography for future reference (Hutchinson 1970). Yet, it can be used for research purposes in any field that needs to compare different movements; productivity research, medical research, sociological and anthropological research, robotics, and a lot more (Rickett 1996).

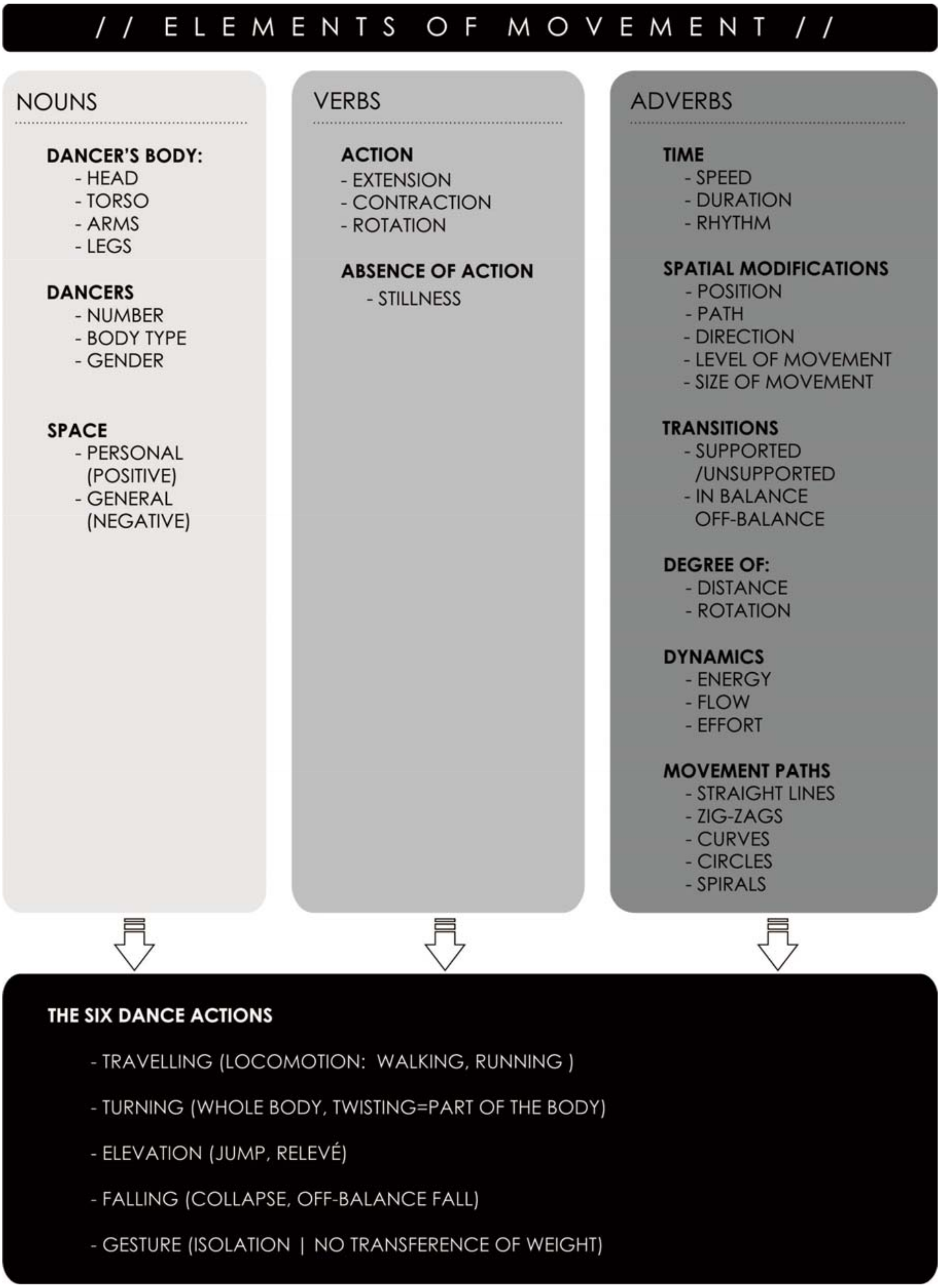


Fig. 9 Elements of movement according to Rickett (1996) and Hutchinson (1970).

2.2 Dance Animation and Inverse Kinematics

Visualising dance as animation has been approached in various ways and for different reasons. Firstly, it was necessary to represent dance scores in a friendly way for the choreographers and dancers. Moreover, choreographers needed a tool to explore different movement patterns for their performances and also be able to store them for later use.

The difficulty to use and understand a dance score made it necessary to invent other easier and faster ways to represent dance, such as **specialised animation software**. The 'LabanDancer' for Labanotation offered such opportunity for dance scores that have been edited with 'LabanWriter' (Wilke et al. 2005). The 'LabanDancer' is based on a deformable, polygonal mesh model, controlled by a hierarchical skeleton. Keyframe animation channels control the angles of the joints, while four inverse kinematic chains drive the individual limbs (legs, feet, arms, hands). The dance score is parsed into three streams; gestures with no weight-bearing, support changes and a generic stream that deals with the use of floor plans, repetition of a sequence, and so on (Wilke et al. 2005). Moreover, the algorithm used for human locomotion (Van de Panne's algorithm) achieves a smooth transition from walking to running, jumping, falling, etc.

The logic behind the **inverse kinematics** technologies is that inverse kinematics interpolates the angles of all the skeleton's joints, given the desired positions of parts of the body. As opposed to forward kinematics, where the angles of all joints are known and the positions of the limbs have to be calculated (Wikipedia: Inverse Kinematics).

Another animation software is 'DanceForms' that offers choreographers and dancers the chance to experiment with patterns of movements in animated human figures (Fig. 10-13). This tool gives them the chance to edit choreography before working with real dancers. The difference between 'DanceForms' and 'LabanDancer' is that in the former, movement is not generated only by a dance score, but also by the use of readymade libraries of animated movements customised for dance (both classical ballet and contemporary dance). Again, a keyframe animation approach is used for the composition of the choreography, while a flexible set of controls is used to refine the different postures (Calvert et al. 2005). Movement can also be seen as a dance score and modified through it (Fig. 13).

THE INTERFACE OF 'DANCE FORMS' SOFTWARE

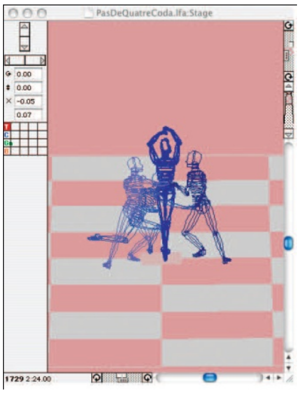


Fig. 10 A stage window for composing multiple dancers.

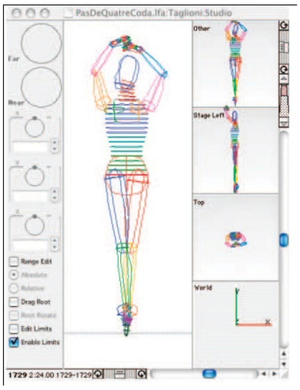


Fig. 11 A studio window for creating particular body positions.

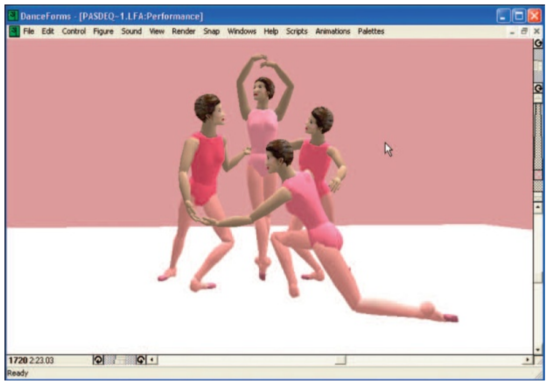


Fig. 12 A rendered performance window.

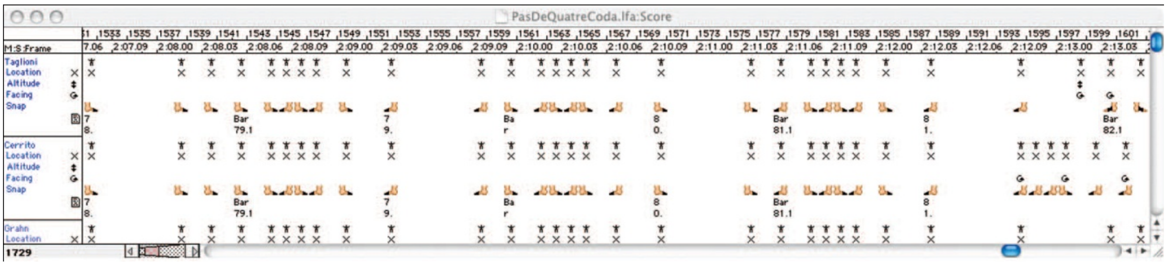


Fig. 13 A score window to show how each dancer moves over time.

Nevertheless, creating believable human motion from keyframing and symbolic representations requires a highly sophisticated model of human movement. According to Michael Girard, digital artist and software designer, 'human *figures have very strong emotional and psychological qualities'* (Kaiser 1988). Yet, how can animation software visualise the muscular experience and the expressive power of the moving body? How would the optimisation of movement that is controlled by our nervous system be incorporated in a simulation of human movement?

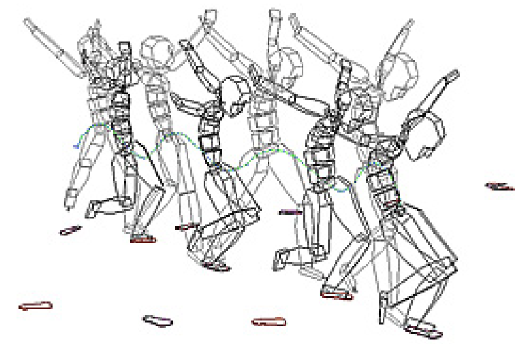


Fig. 14 Biped's motion created in 'Character Studio'.

In cartoon animations, a great number of animators fill the gaps between the different frames using their instinct about motion, instead of mathematical expressions and physically-based dynamics of movement (Kaiser 1988). Trying to produce the same results with computers and automated processes is far more difficult to define. Human movement does not only have acceleration and gravity. It also has a very complex structure, since there are intricate dependencies between all the parts of the human body. Considering the obstacles and the disadvantages of inverse kinematics, interest gradually shifted towards Motion Capture Data, explained more thoroughly in 2.5.

2.3 Video

Fig. 15 Snapshots from the film 'Pas de deux', Canada, 1968

Video serves as fairly accurate medium to record and visualise dance. It is mainly used for making an archive of performances and dance rehearsals that can be later accessed by choreographers and dancers. It can also be used to monitor one's progress in dance or to record random ideas in choreography.

Except for the pure recording of dance there have been some creative approaches of the use of video in dance. The collaboration of the choreographer Merce Cunningham and the musician John Cage for the creation of 'Field Dances' can be regarded as such (Rickett 1996). The final result was a collage of dance presented from different perspectives and distances, fragments of interviews and shots of Cage playing the piano.

'Pas de deux', a 1968 film by Scottish-Canadian director Norman McLaren, is another inspired example of visualisation of dance (Fig. 15). It was filmed on high contrast film stock with very strong side lighting. This was intensified by step-and-repeat printing on an optical printer, letting the movement leave its traces behind after its completion (Wikipedia: 'Pas de deux').

Although video is a medium easy and fast to use, it presents some disadvantages in terms of visualising dance. When recording dance to look back at it in the future, if there are mistakes during a performance, those are later archived and erroneously considered parts of the original dance conception. Moreover, a camera can record a single, specific point of view at a time, excluding others. This can become ineffective in the case of performances with multiple dancers, when some dancers may obstruct the dance movements of others. Even with long shots and multiple cameras, a camera still cannot see what the eyes can see and cannot record the dynamics of dance (Rickett 1996).

2.4 William Forsythe's 'Dance Geometry' and mixed media

William Forsythe is a renowned choreographer, based in Germany, whose interpretation of dance and choreographical approach has captured the attention of a great deal of architects, media specialists and educators. What makes his work worth examining is how intertwined the acts of drawing and dancing are for him. To that his inspiration derived from today's digital technology and algorithmic processes should also be added (Kaiser 1999a). In the following chapter his analysis principles, the improvisation techniques used for his performances and the outcome of his collaboration with architects and digital artists for the visualisation of dance in 'Synchronous Objects' are explained.

Basic elements of Forsythe's technique are **isolation** and **decentering.** As Boenisch points out in his article about William Forsythe and the *'equations of bodies'*:

'Any symmetry and rectilinearity are ignored, as were even the most ***basic sensomotoric and somatic logics and hierarchies****. The muscles and joints of these moving bodies indulged in what appeared as an uncontrolled* ***flow*** *of disfigured mimics, gestural* ***deformation****, a* ***dislocating*** *bending of the joints and the* ***extremities*** *in physiognomically impossible manners'* (Boenisch 2007).

The **aesthetic principles** followed in such a new way of dancing differ much from the values of classical ballet, despite the fact that the dancers of his company come from such a background. More precisely, the simple, smooth movements of classical ballet, which involve formalised transitions, are replaced by unstable, complicated movements, which no longer focus on the result, but on the process of it.

For Mattingly (1999) the choreography of William Forsythe shares a lot of common features with the architecture of Frank Gehry (Figs. 16& 17). In fact, both use 'tilted' and 'distorted' forms, making their work to be labelled as 'post-modern' and 'deconstructivist'. Interestingly, the architect Robert Maxwell describes deconstructivism in a way that can be referred to the work of both Gehry and Forsythe.

'It is unusual, often disquieting. It experiments with the limits of the ugly and the beautiful, and rejoices in intrusions, collisions, rotations and displacements'.

(Maxwell 1993)

Forsythe borrows some of the processes and the vocabulary of computational technology and reinterprets them from the scope of choreographer. His analysis seems to be useful for both choreographers and architects. For the former his method encourages new ways for the composition of dance movement, beyond the formalistic restrictions of precedent dance styles.

Fig. 16 William Forsythe's 'Eidos'.

Fig. 17 Frank Gehry's Walt Disney Concert Hall.

On the other hand, for the architects it suggests an interesting and creative way to explore space, by learning from the body's potential, within the frame of design and computational technology. More precisely, computational design can use these resultant interpretations to create spaces emerging from dance. This exchange appears to be very promising in both fields as choreographers could consider algorithmic processes as a generator for their dances (Kent and Kaiser 2000) and architects can generate forms from dance.

2.4.1 'Improvisation Technologies'

Fig. 18 Parallel Shear.

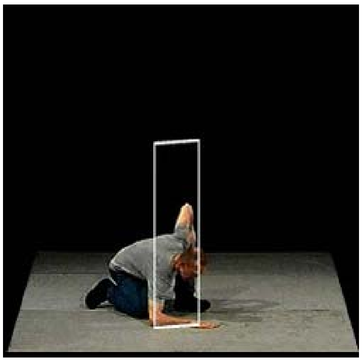


Fig. 19 Extruding Planes.

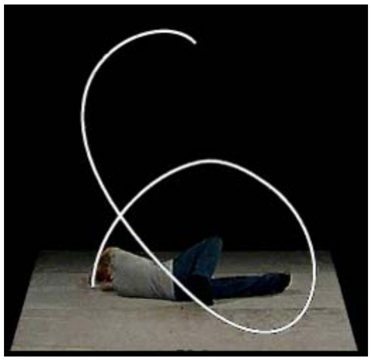


Fig. 20 'Collapsing' points.

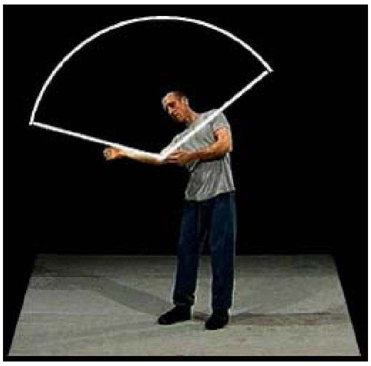


Fig. 21 Rotating lines.

Fig. 22 Curves.

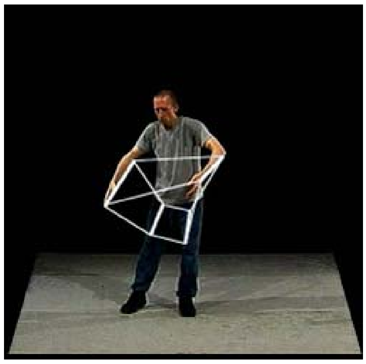


Fig. 23 Volumes.

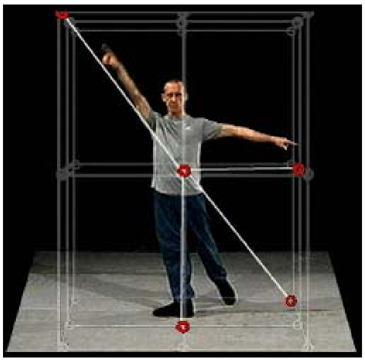


Fig. 24 Laban's orientation of limbs

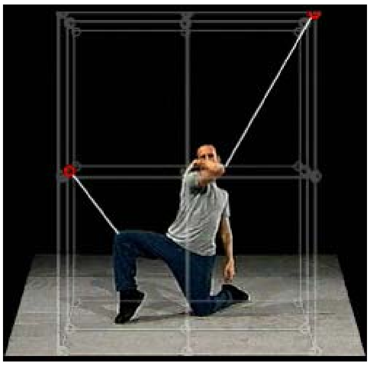


Fig. 25 Forsythe's orientation of limbs

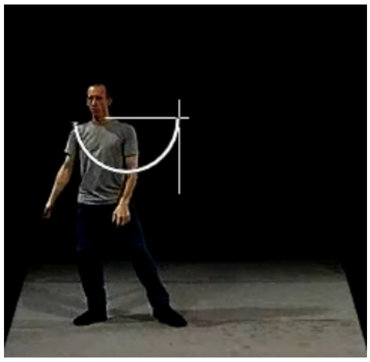


Fig. 26 Forsythe's writing ('U-ing')

After working with ballet dancers for more than 15 years, Forsythe realised that ballet dancers are trained to understand chorographical movement by matching lines and shapes in space. So, he analysed dance movement into **points, lines, planes, volumes** and started composing choreographies by using processes such as **rotation, extrusion, inscription, folding, unfolding**, etc. Clarifying that there is an infinite number of possible movement combinations, restricted only by the physical structure of the human body.

His choreographies are not prescribed. Instead, they derive from improvisation techniques. More specifically, the dancers are given directives called 'U-lines' from which they will generate movement phrases. These may consist of **short phrases** to interpret (e.g. I'm not talking to you, You meet yourself, Cheers you up, To spite you), **mathematical terms** (e.g. divides, delineates, functions, planes), **verbs** and **adjectives** (e.g. deviate, follow, reject, implode, partial), and **computational operations** (e.g. distortion operations, recursive algorithms) or almost nonsensical phrases (e.g. U invert difference, U arc indivisibly, U project solids, U solidify angles, U extend impulse) (Spier 1998).

In order to teach all the previously mentioned principles and ideas in Frankfurt Ballet dancers, Forsythe needed a system to visualise them. His interest in computational technologies lead him to the development of a training tool for dance called 'Improvisation Technologies' (published in 2000), where lines, curves and volumes are superimposed on recorded educational videos to reveal the geometrical structure hidden behind the dancing movement. The CD-ROM is divided into 60 video chapters, consisting of lecture demonstrations in which Forsythe shows the essential principles of his improvisation techniques (Birringer 2002).

Forsythe trains his dancers to imagine trails in space (Figs. 18-26), which are implied either by the currently occurring movement or by the one left behind. They also learn how to manipulate and transform this imaginary geometry, thus emphasising on the space created by the moving body, rather than the space occupied by the body itself (Kaiser 1999b). This idea of the space created by movement is explored later in this research, within the frame of parametric modelling.

2.4.2 'Synchronous Objects – For One Flat Thing Reproduced'

It is also worth mentioning the collaboration between William Forsythe and The Ohio State University's Advanced Computing Center for the Arts and Design (ACAD), for the creation of an interactive, screen based project called *'Synchronous Objects for One Flat Thing, reproduced'*. This project has become a point of reference for the development of this research, in terms of the visual representation of dance.

The aim of 'Synchronous Objects' was to investigate and reveal the deep structures of the choreographic thinking of William Forsythe in his work 'One Flat Thing, reproduced' [OFTr]. In order to achieve this, more than thirty researchers from different backgrounds (architecture, design, dance, cognitive science, computer science, philosophy, geography, statistics, etc.) collaborated with dancers and presented the outcome of their research by using 3D animation, annotation, and interactive graphics (Palazzi et al. 2009).

The choreography was performed by seventeen dancers among a grid of twenty tables (Fig. 28). The collected data was divided in two sub-categories; the **spatial data** (coordinates of points for each dancer) and the **attribute data**. The latter were organised by the researchers into three analysis systems for the interpretation of OFTr; the **movement material**, the **cueing**, and the **alignments**. The movement material includes the sets of choreographic sequences that the dancers used when they performed, while the cues between them affected the course of the dance. Finally, the alignments refer to Forsythe's analysis of movement, and the geometries involved in OFTr.

After processing the previous data, through the different perspectives of this multidisciplinary group of researchers, 'Synchronous Objects' was created. This was the name given to the twenty different visualisation techniques and tools that have been invented. There are 'objects' that visualise cues (such as cue annotations, cue visualiser, counterpoint tool, statistical counterpoint, cue score), others that represent alignment in 2D and 3D space (alignment annotations, 3D alignment forms), video related tools (video abstraction tool, difference forms, noise void, center sketch), 2D interactive graphics (generative drawing tool), and also 3D representation techniques (movement density, furniture system, motion volumes) (Fig. 27-34).

To conclude, 'Synchronous Objects' demonstrated ways to quantify complex dance-spatial data and visualise them in either concrete or abstract ways with the use of transformations, derivations and interactive tools (Palazzi et al. 2009). Moreover, these tools have set a graphical vocabulary for dance that can be read and interpreted in an interdisciplinary framework or even been used as a source for inspiration and creativity.

Various visualisation techniques used in 'Synchronous Objects'.

Fig. 27 Front view of the performance.

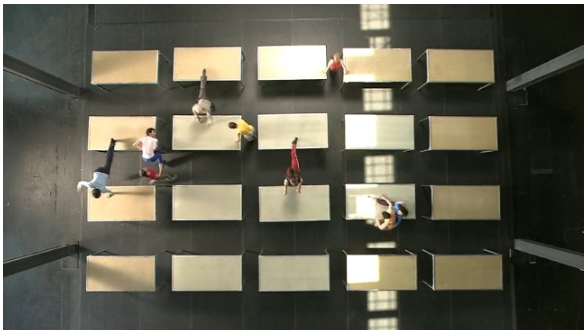


Fig. 28 Top view of the performance.

Fig. 29 Alignment annotations.

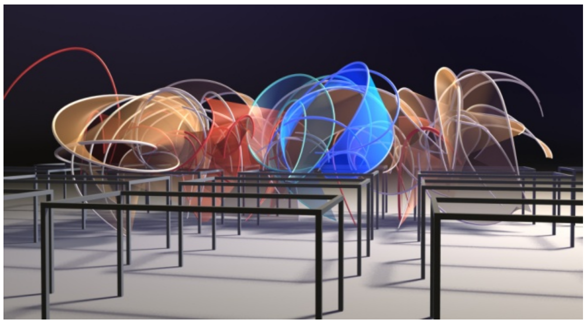


Fig. 30 3D Alignment forms.

Fig. 31 Cue annotations.

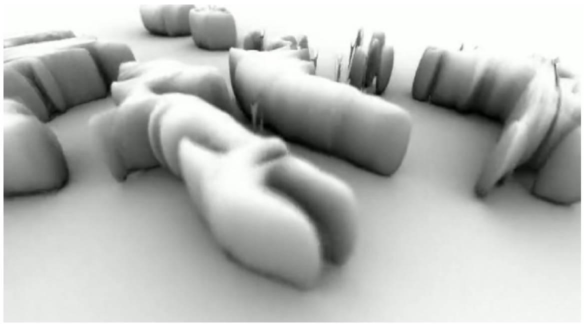


Fig. 32 Motion Volumes.

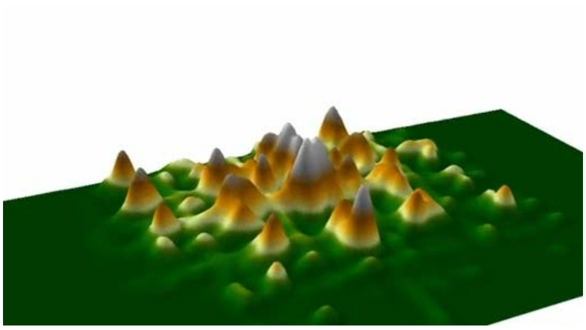


Fig. 33 Movement density.

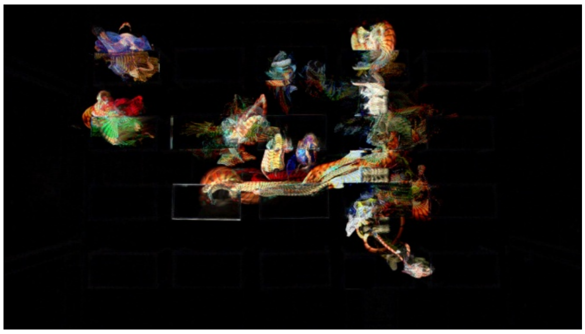


Fig. 34 Difference Forms.

2.5 Motion Capture

2.5.1 Chronophotography – origin of the motion capture

The distant origins of Motion Capture derive from the experiments of Jules-Etienne Marey at the end the 19th century. His scientific interests were quite broad, including anatomy, physiology, physics, etc. and with this multi-disciplinary background he managed to create a series of precise instruments for a variety of purposes; from measuring the pulse to producing animated photography.

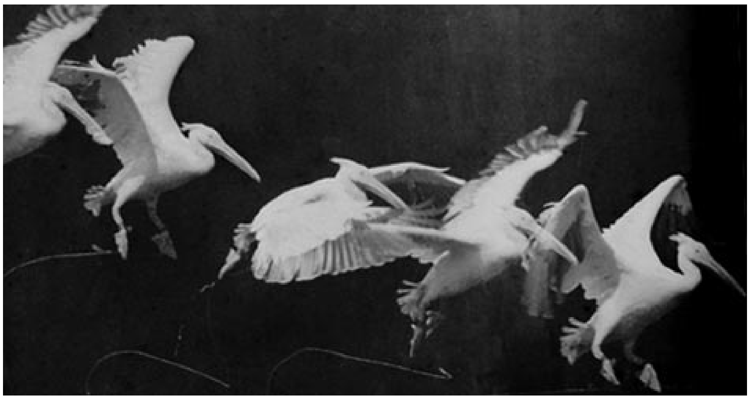


Fig. 35 Several frames of the movement of a flying pelican captured by Marey in a single photo.

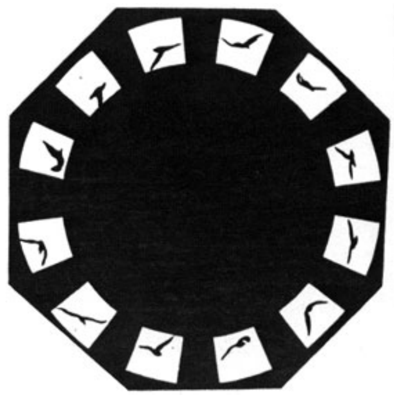


Fig. 36 The photographic gun's plate.

As far as photography is concerned, he achieved visualising movement in two different ways. Firstly, he invented the 'chronophotograph' (1870), a device which could record multiple frames of movement on a single photographic plate (Fig. 35). Since, the latter created confusing effects when the movement took place in the same position, he created a 'photographic gun' (1882), which carried a glass plate instead of the bullets. The result was a plate with twelve different images set around the edge, showing the different frames of a subject's movement (Fig. 36) (Higton 2002).

In order to capture the essence of movement, and study it disengaged from the physical characteristics of the body and the confusing effect it had on overlapping images, he asked his subjects to wear black suits with metal strips or white lines as they passed in front of a black backdrop (Fig. 37-39). This technique allowed him to produce records of the movements of the limbs of people walking or running past the camera. A similar suit is used nowadays too, in order to record the Motion Capture Data. His inventions and techniques allowed a photographic capture of movement over time, laying the foundations of motion pictures, and eventually motion capture.

Fig. 37 Marey's 'Motion Capture' suit.

Fig. 38 Overexposed photograph showing both the body and the markers.

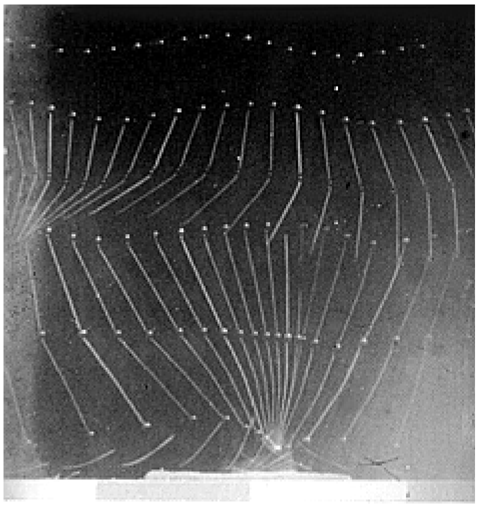


Fig. 39 Photograph showing only the markers.

2.5.2 What is a Motion Capture?

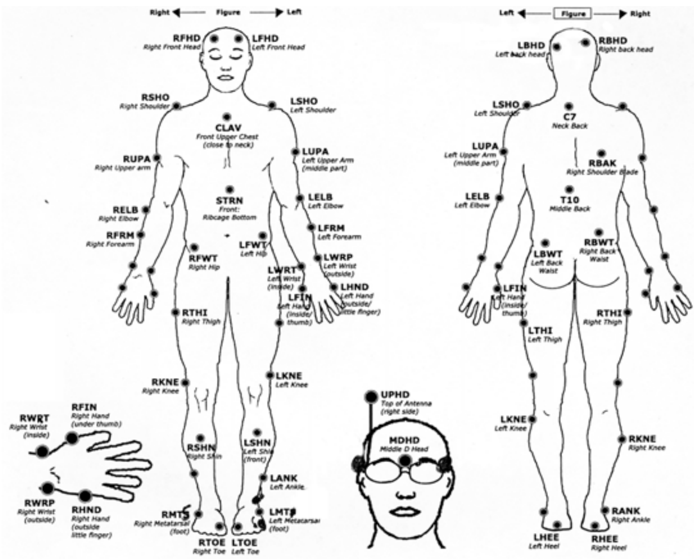


Fig. 40 The labels of the markers positioned on the different parts of the body.

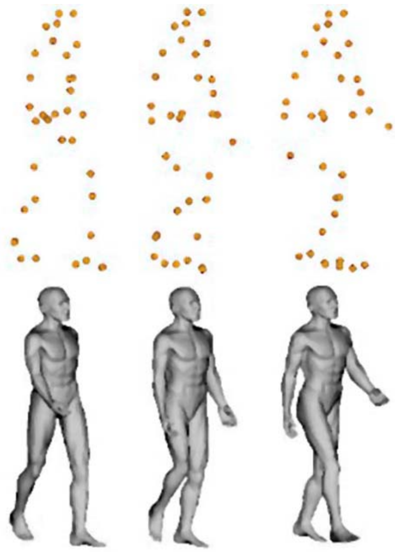


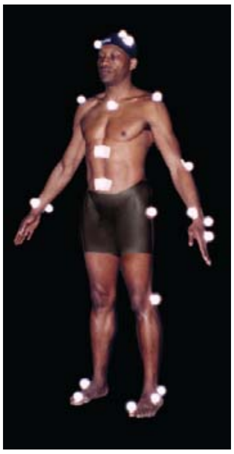
Fig. 41 The 3D markers compared with the equivalent animated motion.

Motion Capture systems provide a method of recording movement from a physical person, in order to translate it onto a digital model. There are three ways for capturing motion; the mechanical, the magnetic and the optical motion capture (Ebenreuter 2005). The mechanical and magnetic motion capture uses an exoskeleton suit with metallic parts that contribute to locating the positions of the limbs and the angles of the joints. The optical motion capture is the most commonly used system, and uses spherical targets, placed on the performer's body.

Fig. 42 A dancer wearing a suit used in optical Motion Capture Systems.

In optical motion capture, the position of the markers is recorded by several cameras and triangulated to provide the 3D coordinates of each marker. This method is very precise and allows recording of very complex movements in detail. However, the original data should be submitted to a lengthy and time-consuming editing before being ready to use as an animation (Ebenreuter 2005).

2.5.3 Applications of Motion Capture

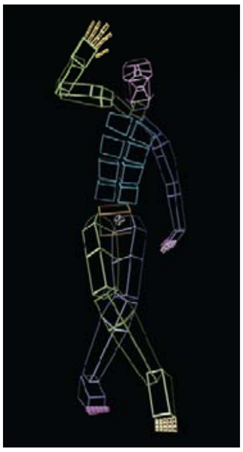



Fig. 43 Bill T. Jones improvising.

Fig. 44 Motion-capture markers.

Fig. 45 Optical conversion to 3D.

Fig. 46 Motion files on 3D skeleton.

Fig. 47 Final drawn body.

The technology of Motion Capture data has acquired a quite broad use. Mostly it is used for the creation of naturally looking animation in film industry, since it was possible to extract complex movements accurately, which are hard to analyse and reproduce with inverse kinematics. They have also been used to create real-time performances with interactive media, or even to study the human movement in medical and sport science (Brown et al. 2005).

A dance-related application of MoCap is ‘*Ghostcatching*’, by the OpenEnded Group. ‘*Ghostcatching*’ is a digital art installation, which is based on capturing dance phrases performed by the choreographer Bill T. Jones, which are afterwards edited, re-choreographed and presented as animated ‘hand-drawings’ (Kaiser 1999b) (Figs. 43-47).

MoCap data have also found application in design industry. The Swedish design group FRONT has developed a technique to translate free hand sketches of furniture into real objects. This achievement has been met by combining MoCap with Rapid Prototyping. By recording pen strokes with MoCap systems it became possible to create 3D digital files (Fig. 48). Afterwards, these were materialised through Rapid Prototyping into real pieces of furniture, made of plastic (Fig. 49).

Fig. 48 Recording pen strokes with Motion Capture.

Fig. 49 Furniture made by Rapid prototyping

To conclude, Motion Capture Systems present a powerful potential for studying movement. According to Michael Girard, digital artist and software designer for animation characters, motion captured movement can be isolated and examined without been influenced by the characteristics of the human body (Kaiser 1998). Thus, Motion Capture Data could allow a more objective view of the form of dance movement, as explored in the following chapter.

3. METHODOLOGY

The wide variety of applications of the Motion Capture Data drew interest and became the starting point for the development of this research. In the following chapter the processing method of the Motion Capture Data, the translation of them into various geometrical forms and the applied transformation techniques are presented. All the previously mentioned steps build-up the framework that will be used later for the development of two case studies. The processing of the case studies resulted in the enhancement of the basic parametric model with parametric construction details, safety checks and fabrication solutions, explained in detail on chapter 4. The program used for the creation of the parametric model is 'Grasshopper', which is a graphical algorithm editor, integrated with 'Rhinoceros' modelling software.

3.1 Translating Dance Movement into Geometrical Form

The Motion Capture Data used for the purpose of this research was retrieved from the database of the Carnegie Mellon University (Carnegie Mellon University 2010). The recording area of motion occupies a rectangular space of approximately **3m x 8m**. Around this area 12 Vicon infrared cameras are placed, which record the movement of **41 markers** located on basic positions on the human body. The cameras are capable of recording 120 frames per second with images of 4 Megapixel resolution. The information that each camera collects is afterwards triangulated in order to get the 3D data. The units used to measure the 3D coordinates are usually in millimetres.

The 3D data is stored in different formats. The files that have been used in this thesis are the *.c3d files, which contain the positions of the 3D markers in space, as opposed to the *.vsk/.v and *.asf/.amc which contain information about the skeleton and the relation of it with the movement data respectively.

The *.c3d files contain various information about the Motion Capture, such as the frame rate, the correspondence between the number of each marker with the parts of the body, the 3D coordinates of the marker during the time and so on. These data needed to be transformed into a format that would later be used for the construction of a static 3D structure deriving from dance movement. Thus, a method should have been developed in order to extend the motion in space rather than time.

Technically, this required the isolation of the 3D coordinates of the markers placed on the human body. For that purpose two external programs have been used. The first translated the data into *.txt file that contained the 3D coordinates of the positions of the markers in time (Fig. 50). The second made it possible to view the structure of the *.c3d file and extract the correspondence between the markers' numbers and their labels (Appendix A) (Fig. 51).

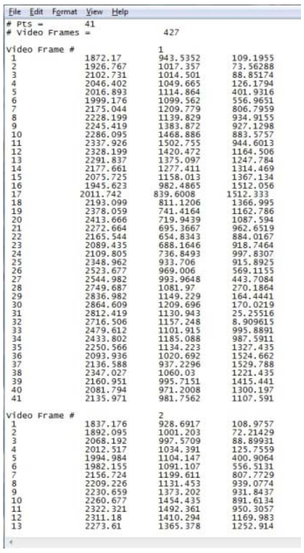


*Fig. 50 *.txt example of MoCap Data.*

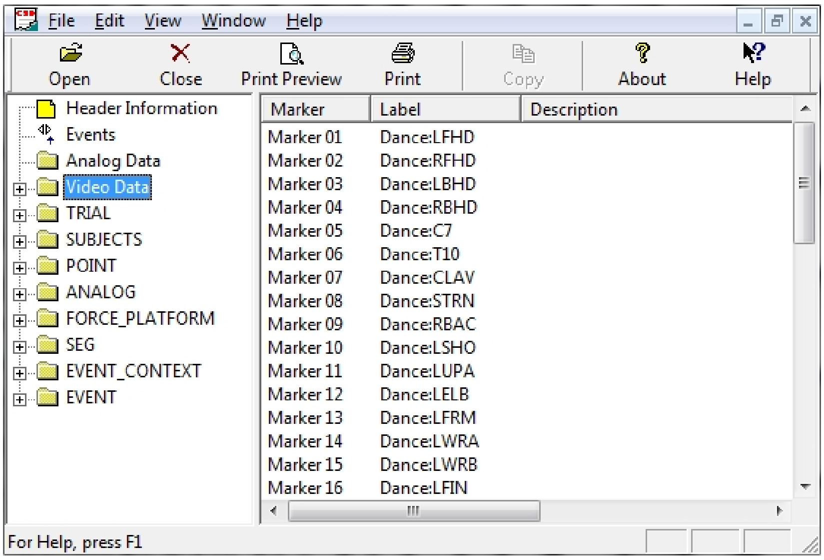


*Fig. 51 The interface of the *.c3d viewer.*

After the previously mentioned processes, the motion data had to be submitted into further editing. More precisely, all the *.txt files that contained the 3D coordinates of the markers had to be purged from all the virtual markers, which were added by the Vicon Bodybuilder Software, during the conversion process to ASF/AMC and they had not been deleted before saving to *c3d (Carnegie Mellon University 2010). The markers sometimes exceeded the 200, when we only need to keep the 41 of the original recording. Afterwards, markers had to be renamed so that all followed a consistent labelling (Stathopoulos 2010a). Since the frame rate of the recording resulted an amount of data (most files exceeded the 1000 frames) that was not necessary for the 3D model, frames have been reduced to one fourth of the original, in order to make their use within the parametric model more efficient (Stathopoulos 2010b). These processes made possible the compatibility of MoCap with parametric modelling, allowing the visualisation and later transformation of the motion's geometry.

Although, there is the possibility to use 41 markers at the same time, for representation clarity of the diagrams presented further down, 14 have been chosen that correspond to the basic joints and parts of the body (heels, knees, pelvis, shoulders, elbows, wrists, and two points placed on the forehead). Nevertheless, the coordinates of the rest are still stored in the data files and can be recalled anytime inside the parametric model.

3.1.1 The Library of movements

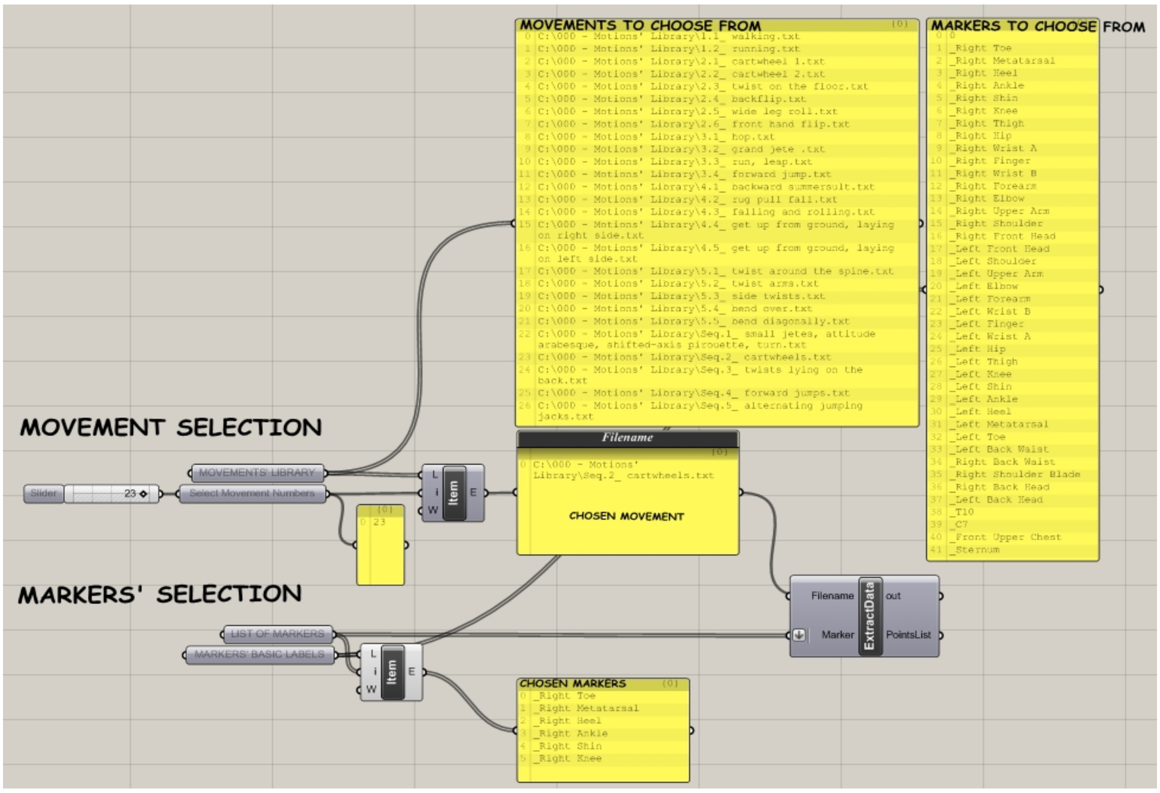


Fig. 52 The selection of movements and markers in the Grasshopper interface.

The following step was to collect MoCap Data and explore them in a systematic way. So, the movements that have been selected to be experimented with have been classified into five categories, following the classification used for the '*action components*' of dance movement (Rickett 1996). The first group includes some **locomotion** actions, such as walking and running. The second one comprises various motions related with **turning** in different directions and planes. The different kinds of **jumps** (e.g. take off from 1foot & land on the same foot, take off from 1foot & land on the other foot, take off from 2 feet & land on the 2 feet) constitute the third category, as opposed to the fourth that consists of **falling** actions. Finally, the fifth group is related to gestures or **'isolation'**, as it is called in dance terms, which refers to movements that take place without any transference of weight or movement of the feet (Appendix B). The previously mentioned actions and the markers that correspond to particular parts of the body can be selected in the Grasshopper interface as shown in Fig. 52.

3.1.2 Positive Space

The positive space refers to the space occupied by the moving body. The mediums used for the visualisation of the positive space are **points, lines, surfaces and volumes**. The methods used for their design, the subcategories of some of them and the difficulties that arose during the process, are described below.

The **points** represent the positions of the markers in space during a time period (Fig. 53). The frame rate of the Mocap indicates how many coordinates of the same marker are recorded per second. This means that if the body or a part of it moves faster than another, then the distance between the coordinates will increase. Similarly, if the body stays still, points are clustered at the same place.

The points are afterwards used for the drawing of the **lines** (Fig. 54). Those are actually curves created from control points arranged according to the order of the points in time. Although, it would have been slightly more precise to create an interpolated curve through a set of points, the program presented a difficulty to draw the curves with that method. However, the dense spacing of the points

Fig. 53 Points cloud.

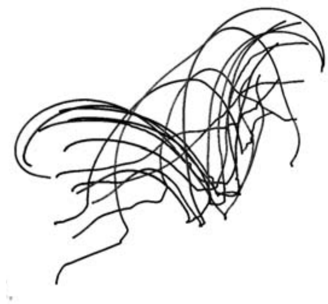


Fig. 54 Lines.

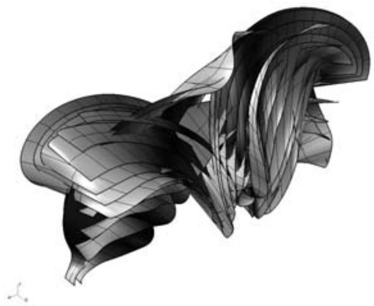


Fig. 55 Surfaces by symmetrical limbs.

Fig. 56 Surfaces by adjacent joints.

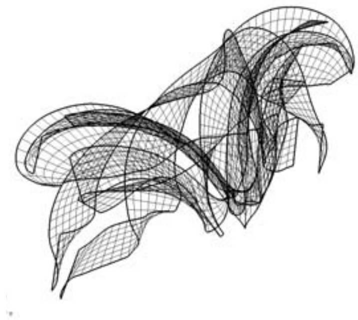


Fig. 57 Grids.

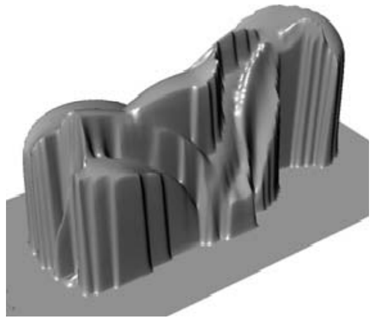


Fig. 58 Volume by draping.

contributes to minimize the deviation of the final curve from the interpolated one.

The **surfaces** are geometries deriving from lofting the curves of the movements in various combinations. Thus, they are divided in three subcategories. The first one refers to the surfaces occurring by joining symmetrical parts of the body, such as the right wrist with the left wrist and so on (Fig. 55). Since, the distance between those points may change as the body moves (except for the symmetrical parts that are connected with the same bone, such as the pelvis); those surfaces have variable width. The second category of surfaces is created by lofting the curves of adjacent joints, such as the elbow with the shoulder, the knee with the pelvis and so on (Fig. 56). Thus, those surfaces have constant width. If we apply a grid of horizontal and vertical elements along any of the previously mentioned surfaces the third group of surfaces is created (Fig. 57).

Although, one would expect that lofting all the edge curves of the movement and capping them afterwards would produce the volume of the motion, this proved fruitless because of the non-planar facets of the surface (Fig. 59). The result of this process is a single surface with very interesting sculptural qualities, but also plenty of self-intersections and non-planar edges.

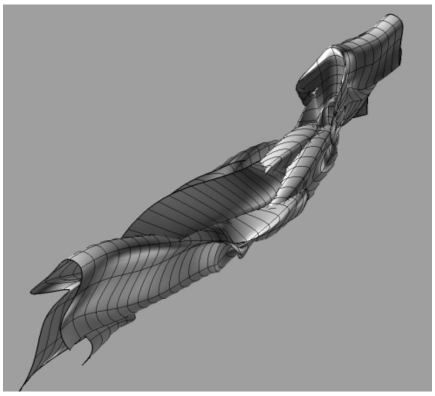


Fig. 59 Lofted movement.

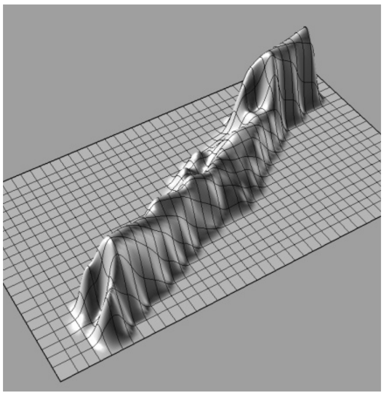


Fig. 60 Draped surface with loose grid.

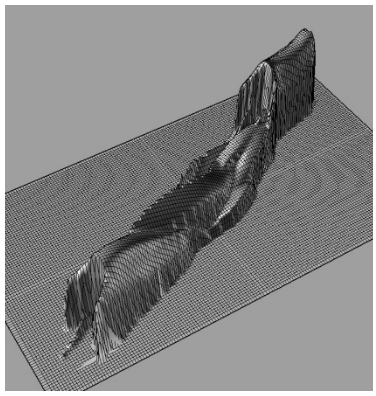


Fig. 61 Draped surface with dense grid.

The design of the **volumes** of the motion became possible with draping a rectangular grid over the lofted surface of movement with the use of 'Rhino' commands (Fig. 58,60,61). The intersection of the object and the points projected towards the construction plane of the object, in the current viewport, define a new surface that resembles an elastic cloth attached firmly onto the object, forming the volume of the movement. The lowest point of the lofted surface defines the base level of the draped surface. Also, the final result depends on the density of the grid. A looser grid forms a more abstract volume of the movement, in contrast to a dense grid which gives more accurate results (Fig. 60 & 61).

3.1.3 Negative Space

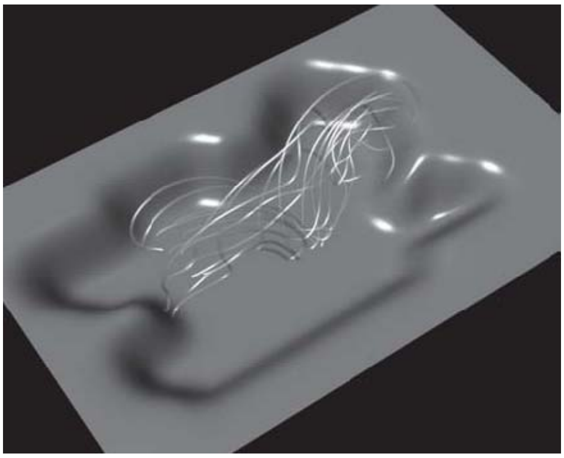


Fig. 62 Surfaces by repulsion.

Fig. 63 Volume by reverse draping.

The negative space refers to the space around the moving body. The negative space has been approached in two ways. Firstly, a surface was deformed as a result of a repulsion caused by the movement (Fig. 62). In the second approach, reverse draping has been performed underneath the lofted surface of the movement (Fig. 63). Generally, in negative space the dancer's movement is used to hollow-out a larger mass of material, like the cutter on a milling machine.

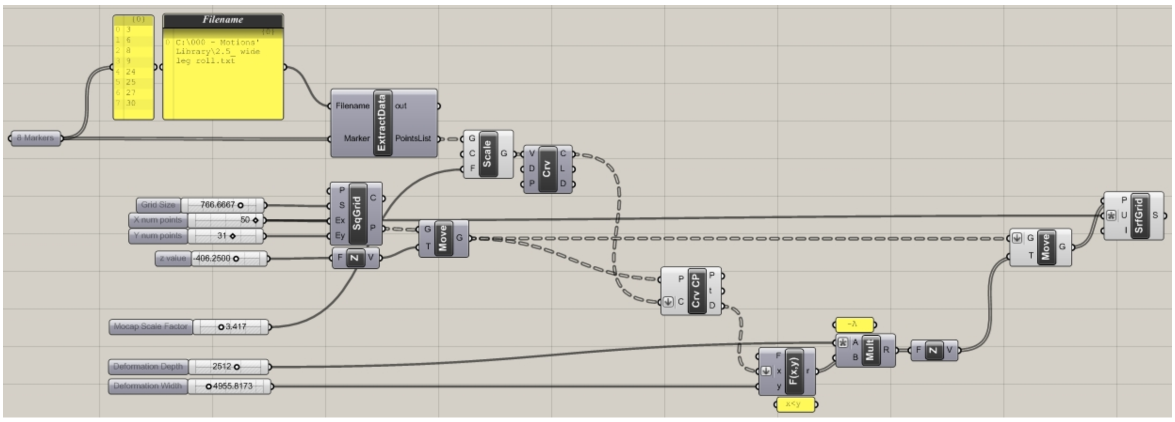


Fig. 64 Grasshopper definition of the surface by repulsion.

In the first case a flat grid of points was drawn underneath the curves of movement (Fig. 65). Then the algorithm calculated the points on the curves that were closest to the points of the grid (Fig. 66). The distance between them was compared with a 'Deformation Width' factor and the points of the grid that were within that limit were moved downwards as much as the user defined, through a slider (Fig. 67). Finally, the moved points were fed as input to generate a nurbs surface from a grid of points (Fig. 68).

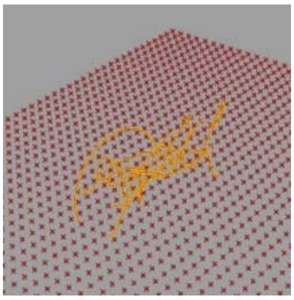


Fig. 65 The grid of points and the movement curves.

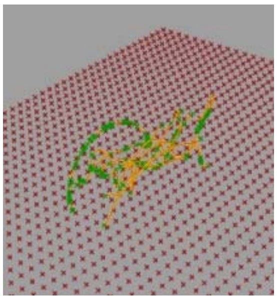


Fig. 66 Closest points.

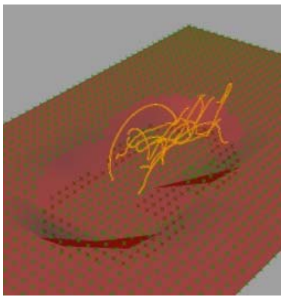


Fig. 67 Move of grid's points.

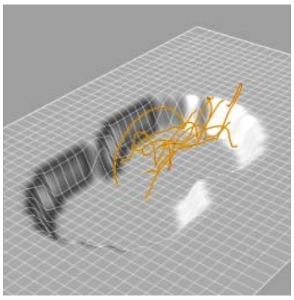


Fig. 68 Final surface.

The parameters that can be modified in this definition vary. Firstly, the size and the density of the grid can be changed, and therefore affect the area of influence and the detail of the deformation accordingly. Then, the deformation width, the deformation depth and the level of the original grid are also controlled by sliders.

The process followed by inverse draping is the opposite of the one described for the formation of a draped volume. In this case the grid is draped from the bottom of the geometry towards the top, resulting in a void that is shaped as an imprint of the movement on the ground (Fig. 70 & 71).

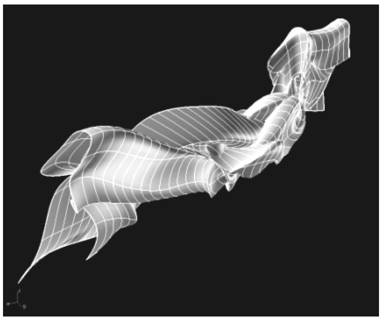


Fig. 69 Lofted surface of motion.

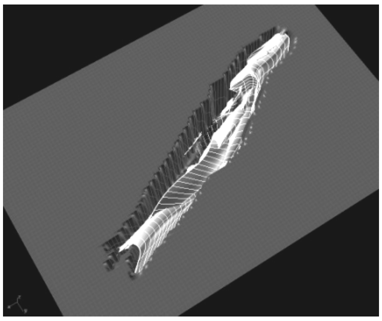


Fig. 70 Reverse draping.

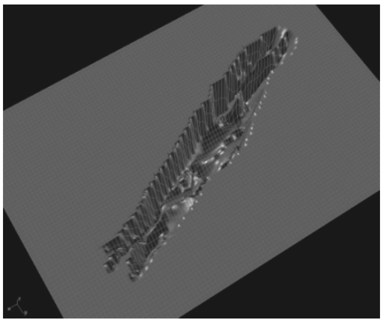


Fig. 71 Negative space.

3.1.4 Discussion

All the previously mentioned visualisation techniques have been applied to a series of movements that have been classified as described in section 3.1.1 and then placed in a catalogue found in Appendix B.

The observation of the results made it clear that one factor that affects the form of dance movement is the location of the markers on the body. In cases when the markers were not placed in accurately symmetrical positions or they had moved during the recording, the final geometry reflected these defects. Also, since the dance movements were not performed by professional dancers, every loss of balance or doubt in movement resulted in inaccuracies that created jerky or wavy lines.

Moreover, dance movement does not always consist of motion, but also stillness. In this case, the representation of it with the current medium resulted in point concentrations in the same place, which can be considered a problem when later these points are connected with lines and these lines are lofted into surfaces. The same idea applies to the gestures, which are movements occurring at the same place. In this case the geometry is formed by the moving parts, while the rest create point clusters (Fig. 72).

Another feature of the geometrical representation of movement is the self-intersections (Fig. 73). For a dancer, every part of the stage is a possible field of action, and they can cross or perform at the same place as many times as they wish. On the other hand, in the geometrical representation of dance, the space is occupied by the previous position of the body. This implies that a whole performance or choreography that is developed in a small area on stage will be 'read' with difficulty in drawings.

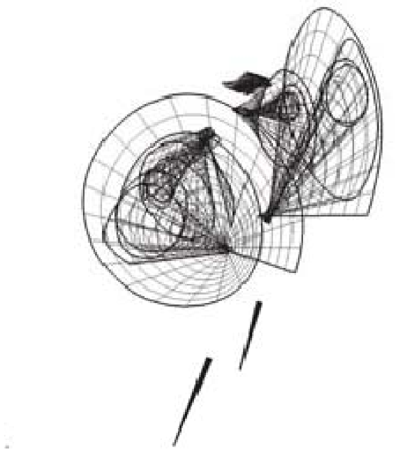


Fig. 72 Twists of arms; Example of movement isolation.

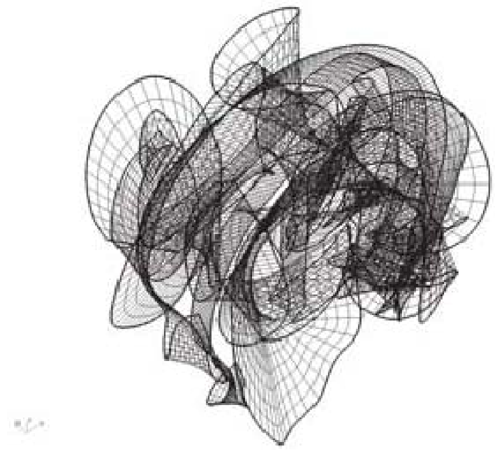
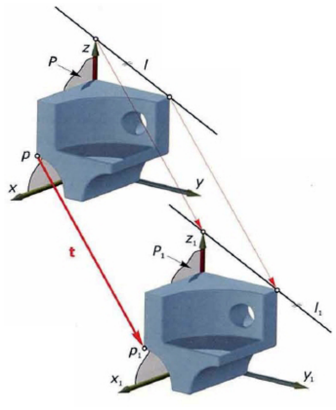


Fig. 73 Back flip; Case of lots of self-intersections.

To sum up, all the techniques used above for the translation of dance movement into three-dimensional form offer the opportunity to understand better the structure of movement, trace some difficulties that occur when an action becomes form, spot some weaknesses of the Motion Capture Data when forming the geometry, and provide a vital basis for the creation of the next section, which refers to the transformations that can be applied on the forms generated by dance.

3.2 Transformation Techniques



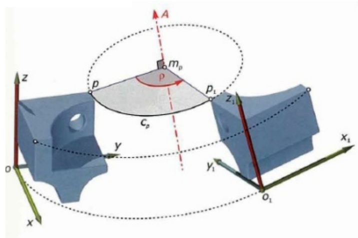


Fig. 75 3D rotation.

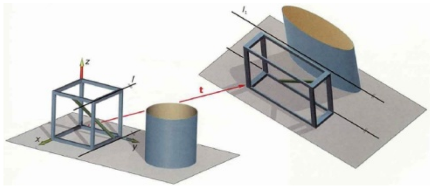


Fig. 76 Independent scaling.

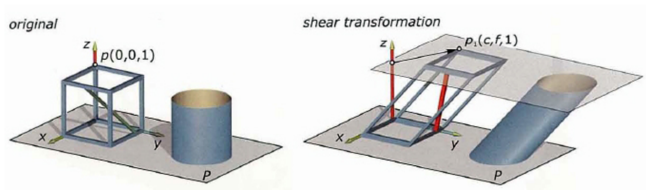


Fig. 74 Translation defined by a translation vector t.

Fig. 77 Shear transformation.

(Pottmann 2007)

Transformations can be applied to the geometries mentioned in the previous section, to adapt themselves to applications with different demands. In the following section the different kinds of transformations and deformations will be explained, and those used for the current project will be highlighted.

The term transformation refers to operations that modify the original geometry by altering various properties. There are plenty of transformation categories, however the most basic ones are congruence and affine transformations. The **congruence transformations** maintain the lengths and the angles of the geometry and in those are included the translation, rotation and reflection (Fig. 74-75). In the **affine transformations** (e.g. Fig. 76) the original shape is modified, but straight lines/planes are mapped into straight lines/planes, parallel lines/planes are transformed into parallel lines/planes and the ratio of the lengths of two line segments on parallel lines is preserved during the transformation (Pottmann 2007).

The affine transformations include the **similarity transformations** which preserve the angles of the geometry, but multiply the all lengths with the same factor, such as uniform scale operation. There should also be added the **shear transformations** (Fig. 77) where one face of the geometry is fixed on the plane where it lies, while two of the coordinates of its corresponding points change, retaining only the value of the third coordinate, thus deforming the geometry's shape (Pottmann 2007).

3.2.1 Description of the process

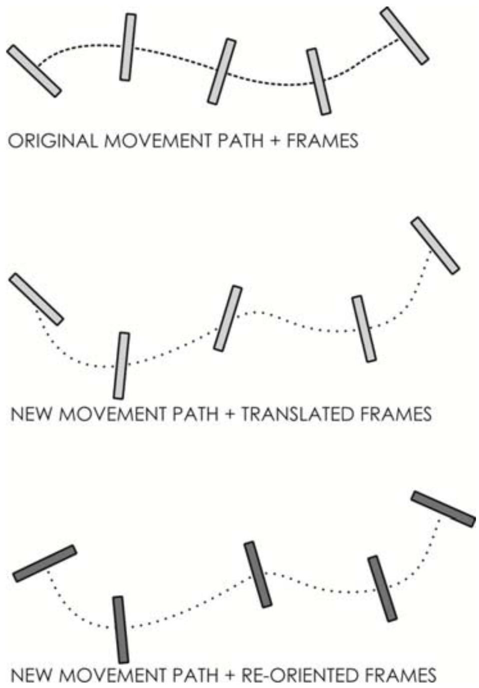


Fig. 78 Different approaches in orienting dance movement.

Considering the use of dance movement as a generative force in design processes, it becomes evident that the geometrical forms described in 3.1 may need to be edited in order to adapt to the requirements of the project. Consequently, some of the previously mentioned transformations should be used, either independently or combined.

The most crucial transformation for the current project is the orientation of movement along a new path defined by the designer. Also, a strategy is needed to combine more movements into a 'choreo-graphy'. Afterwards, supplementary modifications may need to be performed, such as scaling of the geometry in order to be used in a larger project and reflection to get symmetrical movement. Finally, the curves of the movement need to be simplified to give smoother results and also resolve some of the self-intersections.

<u>Orienting a Movement along a Path</u>

One possible way to orient a movement along a path is to maintain the relationship between the parts of the geometry by only translating the frames onto the new path (Fig. 78). Another is to orient every frame of it and consequently deform the original dance. Each method may be more appropriate depending on the intentions of the designer.

In the first case, translation vectors equal to the number of frames need to be applied to the frames. To achieve this, the original path of the movement, which is defined by the movement of C7 vertebra projected on the horizontal plane, is divided by the number of frames (Fig. 79). The same applies to the new path. Afterwards, the points of the original path are connected with the points of the new path through vectors (Fig. 80). These are used later for the translation of the frames (Figs. 81 & 82). Surfaces can also be designed by joining the symmetrical limbs and be simplified if needed (Figs. 83 & 84).

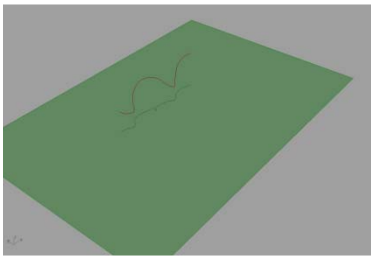


Fig. 79 The movement of the spineprojected on a horizontal plane.

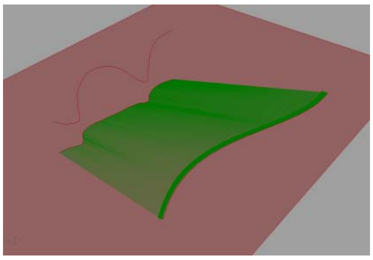


Fig. 80 The translation vectors of movement.

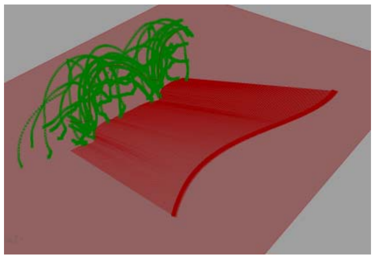


Fig. 81 The points of movement of left and right limbs.

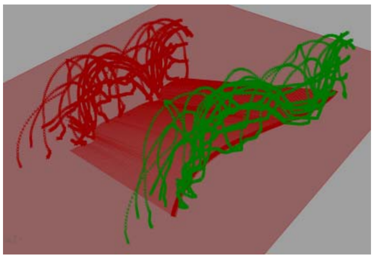


Fig. 82 Translation applied to the movement of left and right limbs.

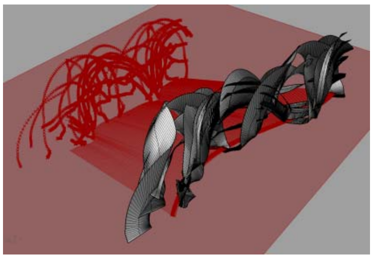


Fig. 83 Lofted surfaces of symmetrical limbs without simplification.

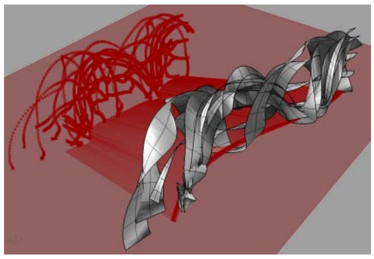


Fig. 84 Lofted surfaces of symmetrical limbs simplified.

In the second method, the markers of the pelvis are projected on the horizontal plane and with a constant vertical direction they define planes that follow the orientation of the body (Fig. 85). Afterwards, the new path is divided by perpendicular planes, equal to the number of frames. Then the planes of the former are used as references to map the movement's frames on the new path's perpendicular planes (Figs. 86 & 87).

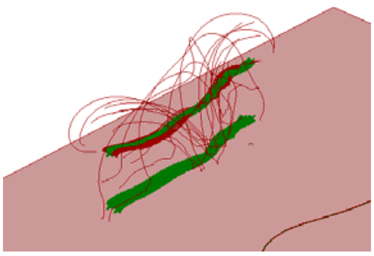


Fig. 85 Planes defining the direction of the body.

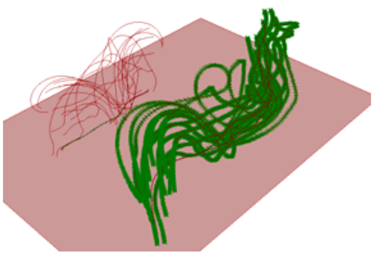


Fig. 86 Mapping of the frames onto the new path.

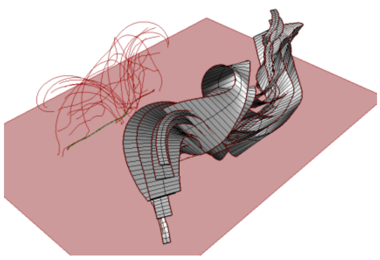


Fig. 87 Lofted surfaces of symmetrical limbs without simplification.

Yet, since the orientation of the body may change, the relation between the frames gets distorted when mapped onto the new path. Hence, the oriented movement does not maintain its original qualities the same way the translated movement does.

Combining Movements into a 'Choreography'

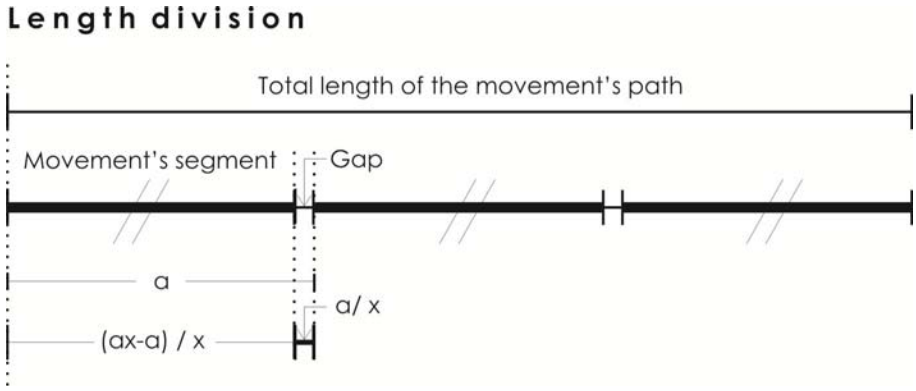


Fig. 88 The logic behind the division of the path and the relation of its elements.

Composing choreography from different elements of movement is also a process that may need to be performed when manipulating dance. The suggested method is the division of the new path into segments equal to the number of movements that need to be combined. However, the connection of the different movements requires an approach that will produce smooth transitions from one movement to another.

One possible solution is the following. The path can be divided into equal segments, with gaps in between (Fig. 88). Then, each individual movement (which consists of sets of points) can be mapped onto each segment. If curves are drawn through all these points, the gaps offer the space needed for smooth transitions.

Since the order of the movement's 3D points agree with the sequence of the performed movement, when it gets mapped onto the path, the beginning of the movement is mapped on the start point of the path, and the end at the endpoint accordingly. Therefore, the correct sequence of movements is inherently reassured. Nevertheless, if the new path is much longer or much smaller than the length of the original movement, then the form of the oriented movement gets distorted and loses its original spatial qualities.

3.2.2 Discussion

Transformation techniques offer a wide range of opportunities to edit and combine movements. Particularly interesting is the similarities of transformation and compositional techniques in design with the compositional devices used by choreographers in dance. When performing, dancers may use different parts of the body, change the level, the direction (translation), the plane or the size (scale) of the movement, repeat a movement (copy), reflect other dancer's movement (reflection) and so on (Rickett 1996).

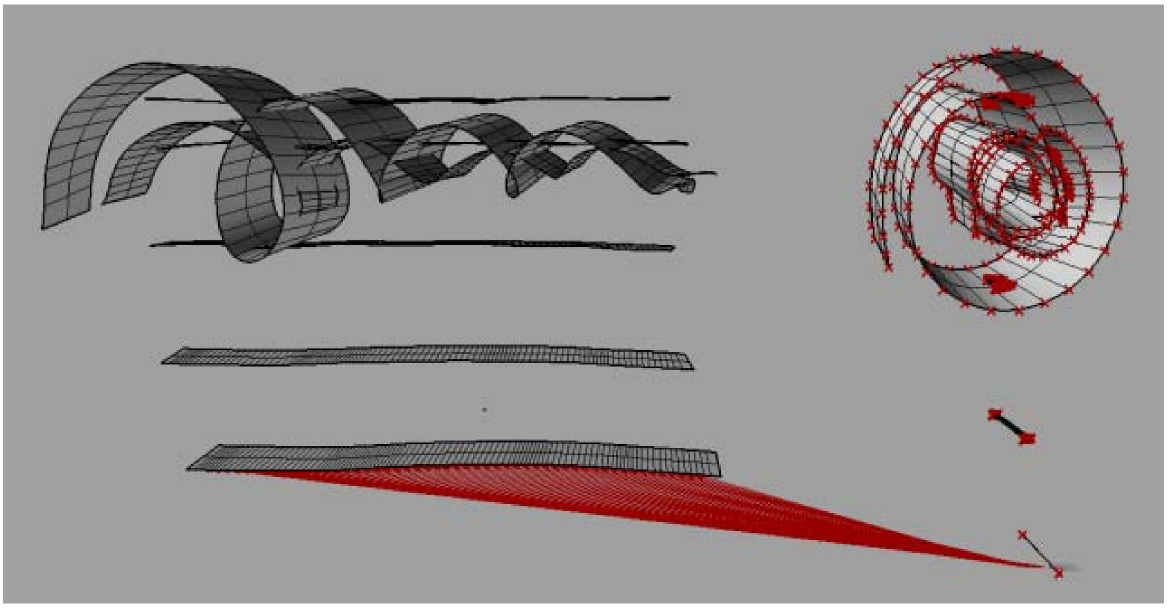


Fig. 89 Twisting of arms translated onto a path.

Some of those compositional devices have a direct equivalent in computational design, while others are indirect and notional. The aim of the transformation techniques presented in the previous section was to offer some basic tools to explore and combine movements, with the minimum possible distortion of the original data. The results in some cases are quite satisfactory, especially when the original movement unfolds in a large area of space. In the opposite case, that is when a movement is performed in the same position, the movement artificially unfolds in space, losing its qualities (Fig. 89).

Crucial in the orientation of movement along a new path, is the way that the original path is defined. In the previous methods the spine projected on a horizontal plane has been chosen. However, originally the movement of C7 in space (instead the projection of it) had been selected, yet this proved fruitless since the translation vectors deformed the oriented movement in the z-axis, which needs to remain unaltered.

Using translation to orient a movement along a new path demonstrates no problems with the orientation of the current material, since the beginning and the end of each movement usually is not the same. Also the movement paths of the original motions are usually linear, so translating them on a curved path works effectively (Fig. 90). On the other hand, the orientation of movement on the circular path deforms the motion significantly (Fig. 91). Yet, if the original motion followed a closed path, the effectiveness of both approaches would be questioned.

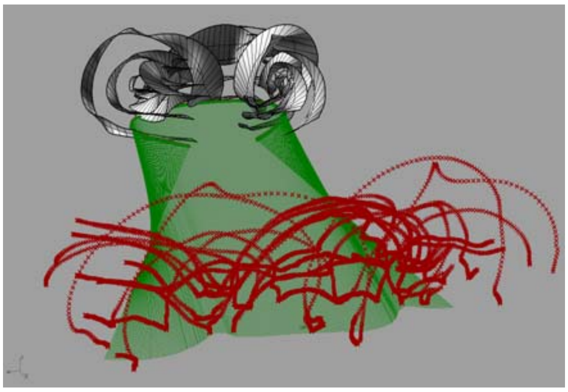


Fig. 90 Translation of movement along a circular path.

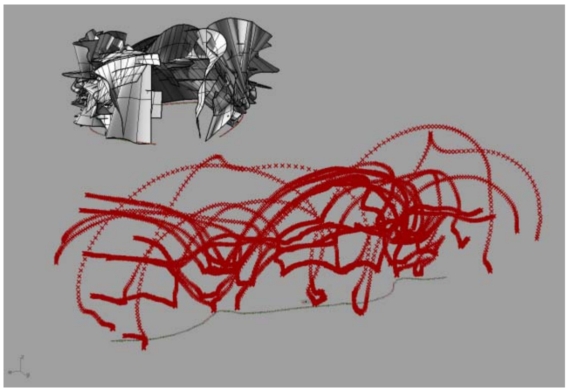


Fig. 91 Orientation of movement along a circular path.

4. APPLICATION OF THE PARAMETRIC MODEL TO A PLAYSCAPE

4.1 Description of the brief

The case study, where the parametric definition is applied, involves the design of a playscape at **Sue Godfrey Park**, Deptford, in the London Borough of Lewisham. The Sue Godfrey Nature Reserve was reclaimed from industrial wasteland in 1984 after lengthy campaigning by local residents. Afterwards, it was used as a Temporary Open Space, until it was recognised as a space with environmental importance in 1996 (Lewisham Council 2010).

The park has a remarkably rich flora and fauna (200 species of wild flowers, shrubs and trees), but the lack of resources results its decay and poor usage of it by the residents of the area (The Deptford Dame 2007).

Fig. 92 The Sue Godfrey Park from a bird's eye view satellite picture.

4.1.1 The Site

Fig. 93 Diagrammatic representation of the current circulation and points of interest at Sue Godfrey Park.

The Sue Godfrey Park is located in a residential area and it is placed adjacent to Ferranti Park, opposite to Laban Dance Centre (Fig. 95). It can be accessed by five entrances around its perimeter and one entrance that connects it with the playground of the Ferranti Park (Fig. 94).

The park measures 5,800 m^2 within which there is an area, of approximately 3,580 m^2, free of plantation. A seating area is placed in the middle of the southern side of the park. Also, remains of a pottery wall can be found along the centreline of the eastern half of the site, as shown in the Fig. 93. The pathways seem to be result of people's everyday use, rather than outcome of a design process, whilst the material with which they are formed is soil with gravel spread on it locally (Fig. 97-99).

Fig. 94 The playground of the Ferranti Park.

Fig. 95 The Laban Dance Centre.

Fig. 96 Passage leading from Ferranti Park to Sue Godfrey Park.

Fig. 97 The south-western entrance of the park.

Fig. 98 The western half of the site.

Fig. 99 The south-eastern corner of the site

4.1.2 The Suggested Functions

The park is currently used as a passage for the local residents, in contrast to the playground of the Ferranti Park which, thanks to its infrastructure, seems to attract more users, mainly school-aged children. Therefore, the suggestion of infrastructure in the current site would be beneficial for the development of the area. The proposal involves the design of a **playscape** for children from 6 to 12 years old, and a **skate park** for older children.

According to the landscape architect Aase Eriksen, a playscape can be defined as '*an outdoor learning environment designed to support and suggest activities that are an essential part of the child's learning and development (social, emotional, cognitive and physical)*' (Heseltine and Holborn 1987, p.15).

There is much scope for discussion and design experimentations around the playscape. Yet, since the case-study is an indicative application of the parametric model on a site-specific project, the proposal focuses on two objects. The first one is a play structure of climbers generated by the experiments on the positive space of dance movement, while the second one is skate-bowl that derives a surface by repulsion of the negative space of motion.

This kind of architecture doesn't prescribe precise patterns of occupation. It encourages the user to participate in the formation of programmatic uses for the structure, and lets the imagination of children choose how such an object could be used.

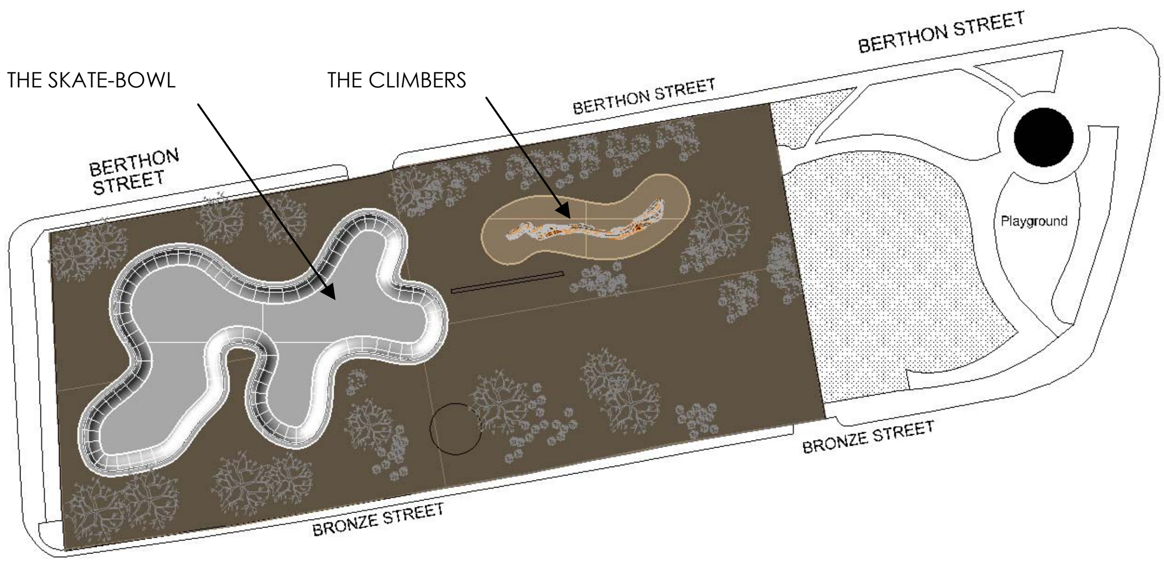


Fig. 100 Site plan – proposal.

4.2 The playscape

The playground is important for the development of children's social, physical and cognitive skills. Moreover, the danger involved in some of the games, contributes to the growth of risk assessment skills. The playscape is a type of playground that is designed to provide a safe environment for play in a natural setting (Playground. In: Wikipedia). In order to create a stimulating playscape, creative design solutions are required. According to Cole-Hamilton (2002) children need both simple and complex environments to play in.

'Designing for play should be seen as an art form – like composing music, writing a new stage play or creating a new painting'. This kind of art though must touch the children through playfulness and imagination, which is the message that children can perceive and appreciate in design (Hendricks 2001).

In the current case-study, dance movement, which has been explored spatially in section 3.1, is combined with parameters such as the **children's age** and functional requirements**.** The aim of this project is to use frozen dance movement in order to create a tactile experience of dance and also to encourage children to familiarise themselves with unconventional geometry through playing.

Fig. 101 Examples of climbing equipment.

4.2.1 Design Parameters – Restrictions

The design parameters that have determined the final design derive from the existing **Safety Standards for Playgrounds**. More precisely the handbooks used for this project are those of the Consumer Product Safety Commission of the United States (ASTM F1487-07) and also the British Standards for playground equipment and surfacing (BS EN 1176-(1-11):2008, BS EN 1177:2008).

The design limitations are connected with the **age** of the users and also the avoidance or **elimination of injuries**. According to data collected from the US hospital emergency rooms by US Consumer Product Safety Commission, the vast majority (79%) of injuries were related to falls from playground equipment to the ground (Handbook for Public Playground Safety, p.3). Other accidents involved entanglement of clothing or other items on equipment such as slides, entanglement in ropes tied to or caught on equipment, head entrapment in openings, impact from structural failure of equipment, and also impact by moving swings. Some of those accidents can be prevented with careful planning, while others depend purely on adult supervision.

To sum up, special attention should be given to the **scale** of each object, the design of the **playground surface**, the **openings** of the equipment, the **layout** of the playground, the **materials** used and the **detailing** of the objects. Generally, protrusions, pinch points, sharp edges and hot surfaces should be avoided.

The Playground Surface

A playground surface is whatever material lies underneath and around the playground equipment. Hard surfacing materials such as asphalt or concrete are unsuitable for a playground. The acceptable materials for protective surfaces are divided in two general categories, **unitary** and **loose-fill**. Unitary materials are the rubber-like, whilst loose-fill include materials such as sand, gravel, shredded wood products, shredded tires, etc. The protective surface should extend a minimum of **1.83 meters** beyond the perimeter of playground equipment.

Detailing

There should be no sharp points, corners, or edges on any components of playground equipment that could cut or puncture children's skin. Consequently, the exposed open ends of all tubing should be covered by caps or plugs, while all corners should be rounded.

Head Entrapment

A component or a group of components should not form openings that could trap a child's head. To avoid this, the distance between any interior opposing surfaces should be either less than **9 cm** or greater than **23cm**. Moreover, the angles formed by the various elements should be greater than **55˚**, unless the lower leg is horizontal or projects downwards (Fig. 102 & 103). An exception to this recommendation can be made if a rigid shield is attached to the vertex between adjacent components and the shield is of sufficient size to prevent a 23cm diameter circular template from simultaneously touching components on either side of the vertex.

<u>Hand gripping Components</u>

Hand gripping components, such as the bars of climbers are generally round in cross section and their diameter should be between **2.4 cm** and **3.9 cm**. Yet, a diameter of **3.2 cm** is considered more appropriate to satisfy the needs of the weakest children of each age group.

Handrails follow the dimensioning of all hand gripping components, and they are placed in different heights depending on the age group that they address to. More specifically, the height for **preschool-age** children should be between **56 cm and 66 cm**, while for **school-age** children it should be between **56 cm and 97 cm.**

Recommended Dimensions for Access Slope, Tread or Rung Width, Tread Depth, Rung Diameter, and Vertical Rise for Rung Ladders, Stepladders, Stairways, and Ramps.

Type of Access	Age of Intended User: 2-5 Years	Age of Intended User: 5-12 Years
Rung Ladders		
Slope	75°–90°	75°–90°
Rung Width	≥ 12"	≥ 16"
Vertical rise (tread to tread)	≤ 12"***	≤ 12"***
Rung Diameter	0.95"–1.55"	0.95"–1.55"
Stepladders		
Slope	50°–75°	50°–75°
Tread Width – Single File	12"–21"	≥ 16"
– Two-Abreast	*	≥ 36"
Tread Depth – Open Riser	≥ 7"	≥ 3"
– Closed Riser	≥ 7"	≥ 6"
Vertical Rise (tread to tread)	≤ 9"**	≤ 12"**
Stairways		
Slope	≤ 35°	≤ 35°
Tread Width – Single File	≥ 12"	≥ 16"
– Two-Abreast	≥ 30"	≥ 36"
Tread Depth – Open Riser	≥ 7"	≥ 8"
– Closed Riser	≥ 7"	≥ 8"
Vertical Rise (tread to tread)	≤ 9"**	≤ 12"**
Ramps (not intended for access by the disabled)* **		
Slope (vertical:horizontal)	≤ 1:8	≤ 1:8
Width – Single File	≥ 12"	≥ 16"
– Two-Abreast	≥ 30"	≥ 36"

* Not recommended for preschool-age children

** Entrapment provisions apply

*** For information on requirements for access to playground equipment by disabled children contact the U.S. Architectural and Transportation Barriers Compliance Board [11].

Fig. 102 Dimensions for access elements (<u>Source:</u> Handbook for Playground Safety, p.17)

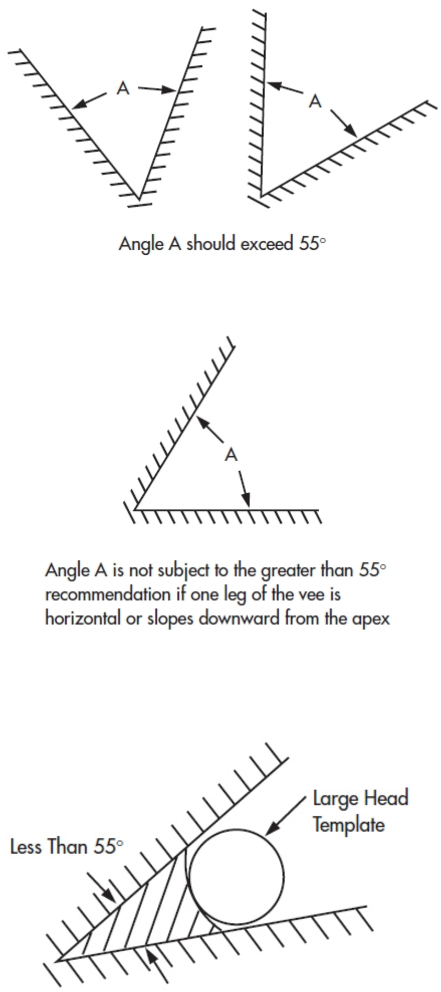


Fig. 103 Recommendations for the angles of the various elements (<u>Source:</u> Handbook for Playground Safety, p.15)

4.2.2 Design Methodology

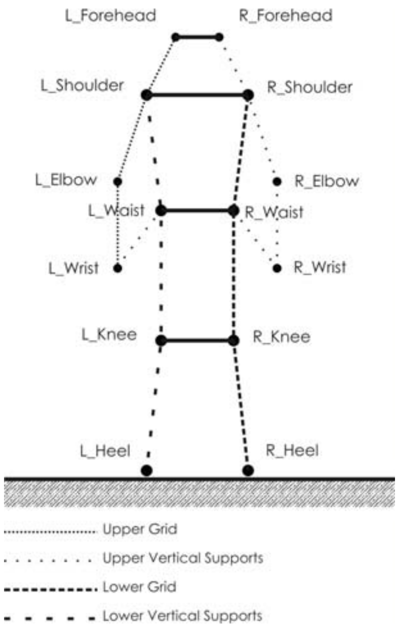


Fig. 104 Scheme showing the connections between the various parts of the body.

The restrictions described in the previous section form the guidelines for the parametric definitions needed for the project. Those restrictions appear in the project in different ways; either they are incorporated into the sliders as minimum and maximum values for the different structural elements, or they appear as additional definitions of new design elements or definitions of analysis tools.

Critical issue for the design of the climbers is the way that the different parts are connected (Fig. 103). In order to address to this problem, **14 markers** have been chosen, which correspond to basic joints of the body. The symmetrical markers of the heels, knees, pelvis, shoulders and head are then connected with **surfaces**. Laterally, the joints are connected with two kinds of **grids** and **vertical supports**. The first grid is formed by joining the right heel, knee, waist and shoulder. The second is created by joining the left wrist, elbow, shoulder and forehead. The left lower body and the right upper body are only connected with vertical supports loosely spaced in order to create open and permeable sides that would add variety to the whole visual impression, and also make the elements coming from the different parts of the body more recognisable.

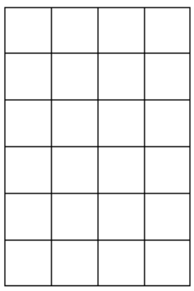


Fig. 105 Squares

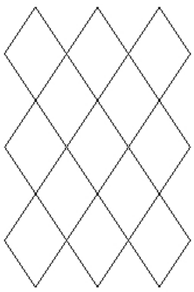


Fig. 106 Rhombus

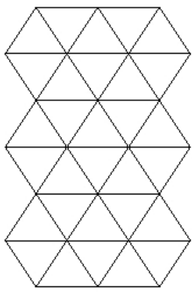


Fig. 107 Triangles

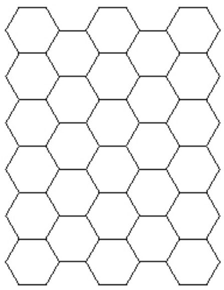


Fig. 108 Hexagons

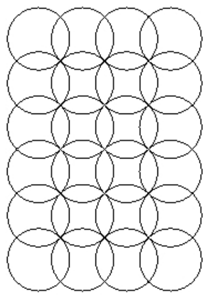


Fig. 109 Circles

Regarding the grids, parametric modelling allows a relatively easy generation of different kinds of grids from two edges. For instance, an orthogonal, diagonal, triangular, hexagonal, or circular grid could be used (Fig. 105-109). However, the complexity of the geometry and also the functionality of the structure as a climber for children required a more simple solution. Thus, the orthogonal grid has been considered most appropriate.

4.2.3 Materiality

The structure of the climbers consists of six basic elements which are described in the parametric definitions below. Those elements are the protective surface underneath the structure, the footings, the primary structural tubes, the vertical supports, the climbing grids, and the climbing surfaces. Finally, in order to check the head entrapment hazard, a definition that checks the distances that are within the limits of danger has been created.

The suggested materials for the climbers, which also affected the methodologies chosen for the elements below, are steel tubes (Fig. 110) for the basic structure, rope for parts of the grids (Fig. 112), recycled plastic sheets for the surfaces of the climbers (Fig. 111) and Engineered Wood Fibre (EWF) for the protective surface (Fig. 113).

Fig. 110 Steel tubes.

Fig. 111 Recycled plastic.

Fig. 112 'Unmanila' fibre rope.

Fig. 113 Engineered Wood Fibre.

The choice of those materials was influenced by both the design parameters described in the previous section (4.2.1) and also by the natural context of the playscape. The steel tubes and the plastic sheets have been chosen for their property to be bent and shaped in complex geometries. On the other hand, the ropes would lighten the structure in terms of loads and also optical effect. Finally, the EWF would be more appropriate than a rubber surface for a playscape located in a natural reserve.

The protective surface definition

The protective surface should extend at least 1.83m from the perimeter of the play equipment. It should also be noted that the dance movement is oriented along a path defined in Rhino by the user. Consequently, this path forms the spine for the solution of this two-dimensional geometrical problem. In order to achieve the desired result, the parametric definition is divided into 4 parts; finding the maximum distance between the curves of the dance movement and the movement's path (Fig. 114 & 115), offset the path curve in both sides (Fig. 116), joining their endpoints with arcs (Fig. 117 & 118), and make a planar surface out of those curves (Fig. 119).

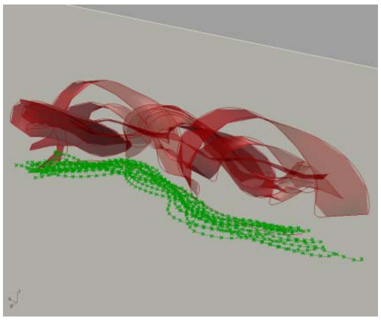


Fig. 114 Projection of the dance curves on a horizontal plane and division into points.

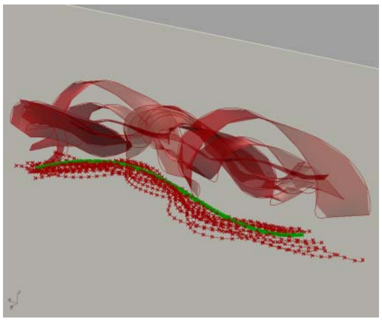


Fig. 115 The closest points of the division points onto the dance path.

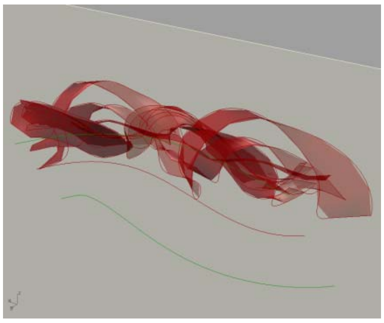


Fig. 116 Offset of the path in both directions.

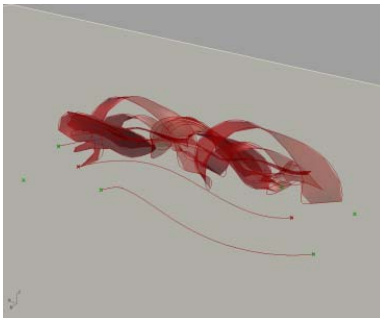


Fig. 117 Finding a third point on the arc.

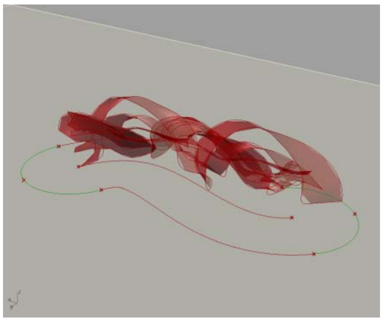


Fig. 118 Making an arc from three points.

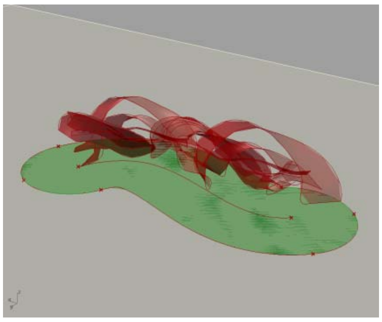


Fig. 119 The final planar surface.

The maximum distance between the projected dance curves and the path is needed because this forms the outer limit of the play equipment. So, the minimum offset of 1.83m is then added to that length and the surface agrees with the safety standards.

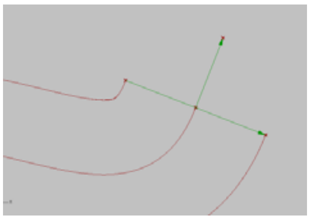


Fig. 120 Finding an interior point for the arc.

For the design of the arc three points are needed; the start and end point of the arc as well as any interior point. The start and end point of the offset curves are used as start and end points for the arc. The same points are used for the creation of vectors from points. The cross product of those vectors with the world z-axis, multiplied by the width of the offset, indicates the direction and distance that the centre of the arc should move to form the third point (Fig. 120). Finally, by joining all the previous edges, a planar surface is produced, which can later be used as a basis for the construction details of the protective surface, depending on the materials used.

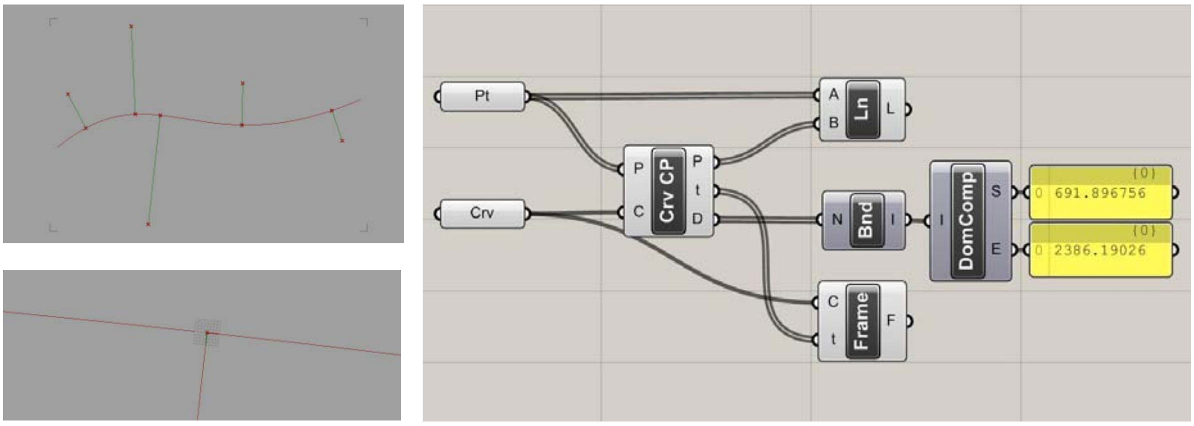


Fig. 121 Finding the closest points on line to points and the maximum distance between them.

Layer 5 | Loose Fill Material for Surfacing
Layer 4 | Rubber Mat (under slides)
Layer 3 | Geotextile Fabric
Layer 2 | 8-15 cm of Loose Fill (gravel for drainage)
Layer 1 | Hard Surface (asphalt, concrete, etc.)

Fig. 122 Installation layers underneath a loose-fill protective surface.

In this case the suggested material is 'Engineered Wood Fibre' (EWF), which is wood, mechanically shredded into sizes and aspect ratios determined by a series of specified sieves, through which the final product must pass. In use, the wood fibres knit together to form a mat that is springy enough to meet ASTM F1292 for impact attenuation, yet firm enough to meet ASTM F1951 for wheelchair access.

Underneath this layer there is a geotextile fabric to separate the soil from the wood fibres and also a roll-out drainage system that assures a playable surface, even after rain. In areas, where the wood fibres can be scuffed away, an additional layer of rubber mats is placed to reassure the safety of the users (Fig.122).

The Footings

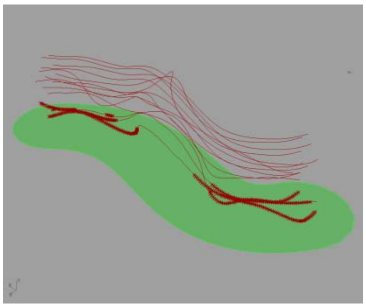


Fig. 123 200 points of lowest z value.

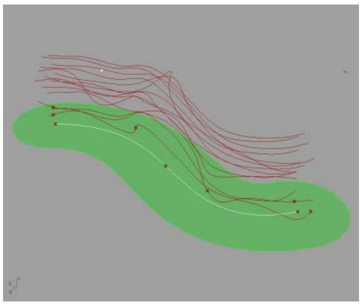


Fig. 124 Three pairs of supports, after the 2nd sorting.

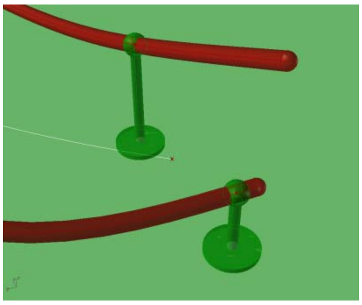


Fig. 125 The detail of the parametric footings.

The human body, from which all these points are derived, is already a highly sophisticated structure which generally establishes contact with the ground through the feet. However, when people perform, they do not necessarily stand on their feet. They may roll on the floor using their back or even use their hands as supports. Thus the points that can be used as supports for the structure can vary.

For the solution of this problem, the curves of all used markers are divided into a sufficient number of points, controlled by a slider. The z coordinate of all those points is sorted from the lowest to the highest, sorting the list of points accordingly. The user can define the number of lowest points that will be used as supports (Fig. 123). Yet the result is not satisfactory and requires further sorting. The problem is actually that at the places where the body comes in touch with the ground, all adjacent points belong to the range of lowest points defined beforehand. In order to get one from each group of points, the movement's path is divided by the desirable number of supports. Then, the closest points to the divisions are selected from the group of lowest points (Fig. 124). At these points it is possible to connect the parametric structure to supports.

An example of such support could be the following. Firstly, it is needed to project those points onto the plane of the protective surface. Within the distance between the original points and the projected, the structure is created. A cylindrical metallic plate is placed at the bottom. At the top a thinner cylinder continues upwards until it reaches the edge of the steel tube of the structure. A metallic ring, coming from the subtraction of a sphere with the tubes of the edges, forms the top part of the joint (Fig. 125). The footings get updated after any change made on the model.

<u>The Steel Structure</u>

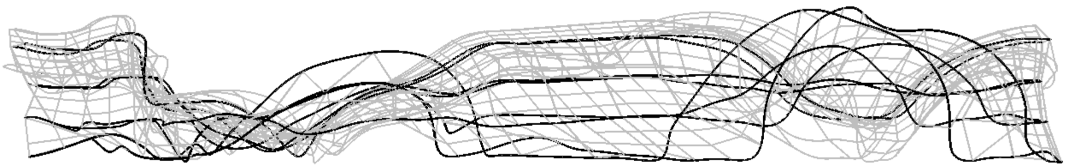


Fig. 126 Front view of the basic steel structure (black) and the secondary structure in gray.

The forming of the steel structure (Fig. 126) is based mostly on the correct arrangements and combinations of lists and data trees. Depending on the number of motions used to form the choreography, these motions should be connected so that the points of the same marker of each motion are merged on the same branch.

Then, it is possible to start elaborating the different parts of the structure. Firstly, the edge curves of the structure are simplified to produce smoother curves, more appropriate for fabrication than the originals. Afterwards, the vertical supports of the structure are arranged as described in the design methodology. Yet, the definition of the grids needs some additional processes.

The edge curves are divided into equal segments and then the points are connected with lines. The division of these lines defines new rows of points that need to be rearranged in a new list, so that the first division of the first line would be connected with the first division of the second one and so on. The final lists of data are fairly complicated, since all the points of the three grids of the right side are combined, in order to form a tree with three levels of branches.

Surfaces

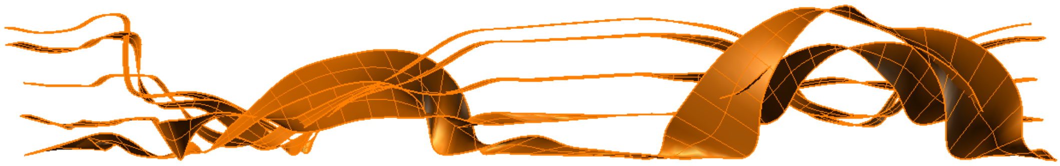


Fig. 127 Surfaces by lofting symmetrical parts of the body.

The surfaces of the structure are produced by lofting some of the symmetrical joints of the body (heels, knees, pelvis, shoulders, and two points on the forehead) (Fig. 127). For the creation of them two lists of curves are needed that contain the curves of the left and the right side respectively. These kinds of surfaces are ruled surfaces that are generated by joining the points of the two parameterized curves (Pottmann 2007). So they get twisted and bent according to the geometry of their edges. It should also be mentioned that by performing a Gaussian Curvature Analysis on the surfaces of the model, the minimum and maximum values of them were almost zero. Consequently, these surfaces could be unfolded into the plane without any distortions, and they could be constructed by flat sheets of plastic. More details about the unfolding and the fabrication of the surfaces are presented at the following section.

Indication of unsafe areas for head entrapment

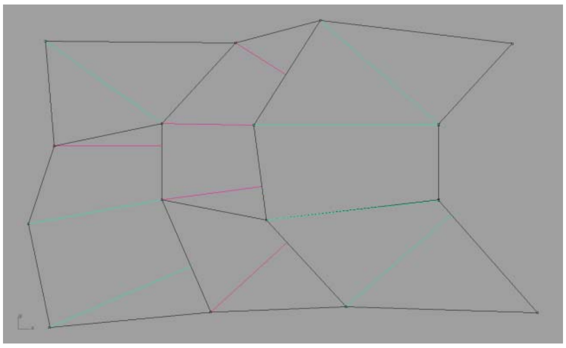


Fig. 128 Horizontal distances between the elements of the climbing grid that are within the permitted limits (cyan) or exceeding them (magenta).

This analysis is performed on the grids of the structure and is divided into two parts; analysis of the distance between the horizontal elements of the grid and analysis of the distances of the vertical elements. The condition that should be maintained in both cases is **9 cm ≥ acceptable distance ≥ 23 cm.**

In order to measure those distances, the closest point on a curve is used. In fact, the distance between the points of the first row/column and their closest points on the curve of the second row/column is measured, and the same process is repeated for all elements. The distances that are within the acceptable limit, and those that exceed it, are coloured with cyan and magenta colours respectively (Fig. 128).

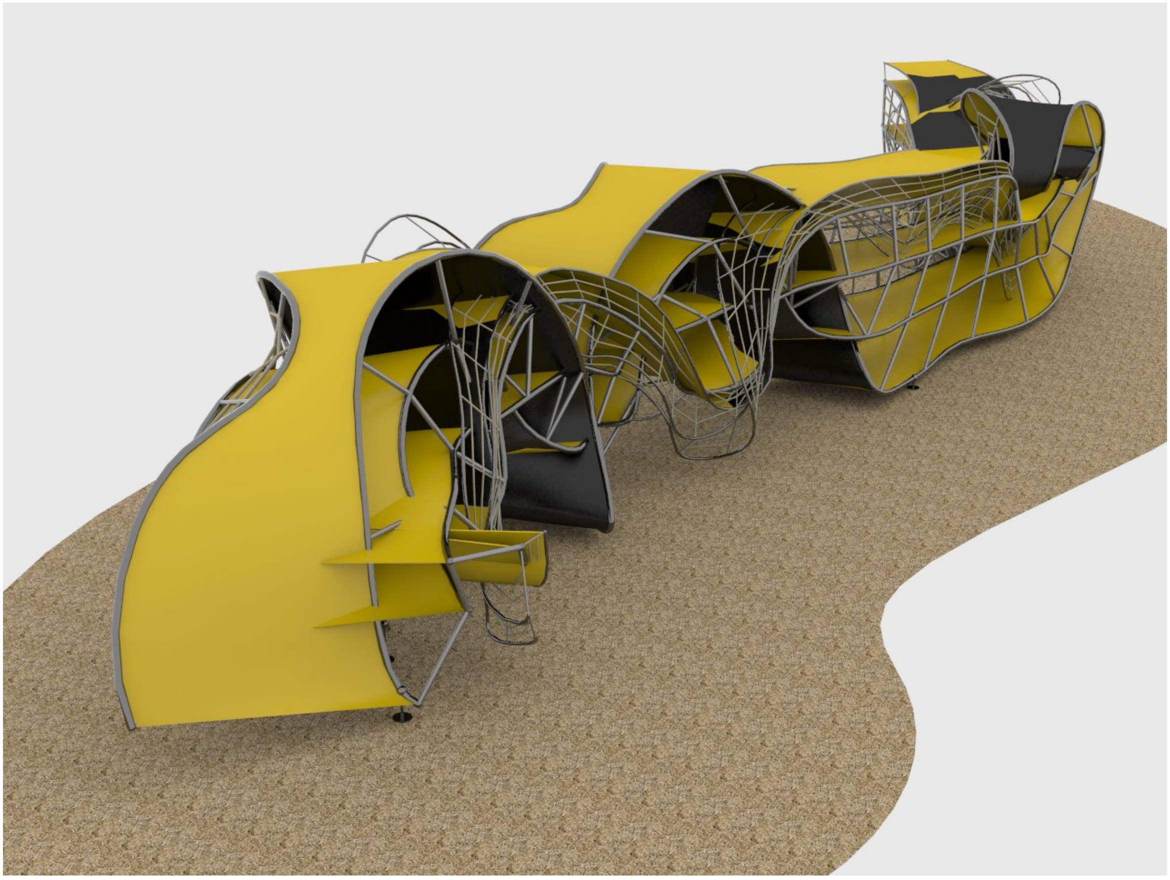


Fig. 129 The climber with all its elements combined.

4.2.4 Digital Fabrication

The complexity of the geometry makes its fabrication difficult to resolve. However, there has been a significant effort to locate or design elements that can be repeated or elements that could be constructed using the same profile. Some indicative techniques that can be used for the construction of the structure involve NC Controlled Pipe Bending (Fig. 130), welding, drilling, laser cutting (Fig. 131), and thermoforming.

Fig. 130 NC Controlled Pipe Bending.

Fig. 131 1.5m x 3m laser cutter.

<u>Footing</u>

Fig. 132 Telescopic footing.

The elements used as supports are described in detail in section 4.2.3. Providing that the final dimensions of the main structure is decided, those elements can be fabricated and be repeated thanks to their telescopic axis (Fig. 132). Therefore, they can be easily adjusted to the various heights of the support points without customisation.

<u>Steel structure</u>

The steel structure consists of pipes with some variations in their radii. As far as fabrication is concerned, the pipes of the edges could be bent with a NC Controlled Hydraulic Tubing Bender. All the rest of the steel structure is straight pipes that are welded on the main structure.

Once the radius of the pipes that form the edges is decided, the radii of the rest of the elements are proportional to this value. The details of the relations between the various elements are described in the table below. All the radiuses are expresses as fractions of the widths of the edges.

PART OF STRUCTURE	RADIUS	NOTES
Upper Body Edges	½ Edge Radius	Metallic fins are welded on the edges of the forehead surface
Lower Body Edges	1 Edge Radius	Metallic fins are welded on all the edges to support the surfaces
Upper Body Vertical Bars	¼ Edge Radius	-------------------------
Lower Body Vertical Bars	¾ Edge Radius	-------------------------
Upper Body Grid	¼ Edge Radius	Drilled at n points (n=the number of horizontal subdivisions for the grids)
Lower Body Grid	½ Edge Radius	Drilled at n points (n=the number of horizontal subdivisions for the grids)

Fig. 133 The basic steel structure (black) with the secondary steel elements (gray) and the ropes (yellow).

The metallic parts of the structure are welded. The parts where the joints are differentiated are the grids where the horizontal elements consist of ropes and they are connected through metallic rings to the vertical bars, and also the joints between the edges and the plastic surfaces that connect the symmetrical limbs.

In terms of detailing, all open pipes should be capped in order to comply with the regulations for the playground safety. There is only one kind of pipe that needs to be capped, which is the pipe of the edges. So again, a repeated element can be used for all openings, which is going to be double the number of curves (to cap the holes of their two edges) and its radius will adjust to the radius of the pipe.

Surfaces

The surfaces need to be processed in three stages. Firstly, flat sheets of plastic should be laser-cut. Then they should be drilled at the points where they will be connected to the steel structure. At the end some of them may need to be bent with thermoforming equipment, depending on the bending ability of the plastic sheet and the radius of bending of the structure.

In order to arrive to the previous results from the three-dimensional parametric model the following course should be performed. Firstly, each surface is unrolled in grasshopper with the use of a VB.NET Scriptable Component (Chalmers & De Leon 2009). The input for this component is the edge curves of the surface and a resolution factor defining the accuracy of the unfolding. Then, the output is a planar surface that corresponds to the bent one (Fig. 134 & 135).

Fig. 134 Perspective of the original surface.

Fig. 135 Top view of the unrolled surface.

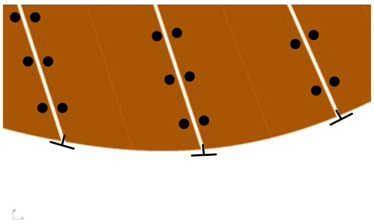


Fig. 136 Schematic diagram of the surfaces connections.

The remaining fabrication processing of the surface is performed on the unrolled parametric surface. Firstly the surface is divided into sub-surfaces. At the {u} direction it is always 1. At the {v} direction there are used half of the vertical subdivisions of the grids (the slider of the 'Vertical Subdivisions' is set to allow only even numbers) so that the subdivisions of the horizontal surfaces are aligned with every second subdivisions of the grids.

By decomposing each sub-surface into its component parts, it is possible to manipulate the edges. In fact, since the surfaces are lofted from the axes of the pipes, a width equal to the radius of the pipes should be subtracted from the edges of each surface, by offsetting the corresponding edges of each sub-surface. The elaboration of the other side of the surfaces is subject to the chosen detailing. In this case the surface is offset and drilled (Fig. 136).

By establishing all the previously mentioned relations, information about the lengths, radiuses and number of elements of the structure in Grasshopper panels can easily be extracted, as well as the edges of the laser-cut surfaces. If any of the parameters of the model change the data on the panels get automatically updated.

4.2.5 Discussion

Adding restrictions to a parametric model to meet the functional requirements of the project revealed some interesting qualities regarding the geometrical representation of dance. In some aspects it met the requirements successfully, in others there was nothing else to be done except for choosing a different movement.

Since the climbers are a game which is inherently risky, the complex geometry of dance succeeded in generating forms that are challenging enough to climb on. Yet, the rigid restrictions of playground safety could not be followed in all cases. Some of the dance movements were inappropriate for this kind of usage, as well as for the creation of a spatial structure from dance in general. Such examples are the gestures which are performed at the same place. Since altering the movement a lot would distort the qualities of movement, transformations in some cases have been considered inappropriate. For that purpose the analysis tools have been created, which allow whether the geometry meets the functional requirements or not to be checked.

The most important operation in the parametric definition is the management of lists of data. In order to make the various parts of the definition work, the sets of points or curves or any other geometry used should be arranged in the appropriate sequence to give the desired results. Unfotunately, Grasshopper fails to maintain the dimensions of the arrays and increases them without increasing the data inside. This results the inability of the program to further edit this data unless it is flattened. However the new list no longer has the attributes of the original list, therefore it needs to be rearranged again into branches. This fact made the progress of the project harder and restricted the possibilities of the parametric model. For example, instead of choosing multiple movements from one definition, this needs to be multiplied as many times as the number of the used movements.

A commonly seen feature of dance forms is self-intersection. This adds difficulty to the fabrication of such a structure. Yet, at this stage of processing, this problem has not been resolved parametrically and is suggested as a subject for future research.

To conclude, the case study offered the chance to develop a technique to deal with a particular problem. But in the parametric model some general principles can be identified, such as the notion of structure and support, that could be followed in other cases as well. By using the transformation techniques or some of the definitions differently, for example scaling the dance movement excessively, the dance movement could generate forms for other facilities or functions and be used as a generator of form in various contexts.

4.3 The skatepark

Skateboarding has become popular in Europe since the 1970s, when it arrived from the United States. Originally it took place in public spaces (streets, squares, public stairs etc.), but from the mid-seventies the first skatepark was built (in Albany, Western Australia) and championships have started to be organised since then (Wikipedia: Skatepark). This activity usually addresses to persons 14 and over.


Quarter pipe


Half pipe

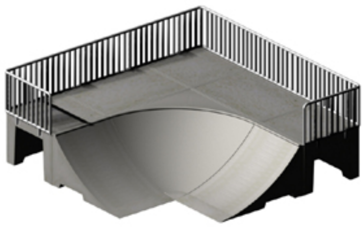

Full pipe


Funbox


Pyramid bank


Flat Bank


Bowl


Quarter Pool


Vert Wall


Rail


Curb Ramp


Spine ramp

Fig. 137 Some of the basic obstacles used in skateboarding. (Source of renderings: www.urbanramps.co.uk).

4.3.1 Design Parameters

Fig. 138 Skateboarder performing tricks at the coping of a skate-bowl.

Skateboarding is classified as an extreme sport; hence facilities for users of roller sports equipment have to be challenging enough to attract the skateboarders. The dimensions of the elements used are rather flexible and varying, while only a few dimensions and requirements have to be met. For this design element the Safety Standards that have been followed are included in the **British Standards for 'Facilities for users of roller sports equipment — Safety requirements and test methods' (BS EN 14974:2006)**, although there is no information focusing on skate-bowls in particular.

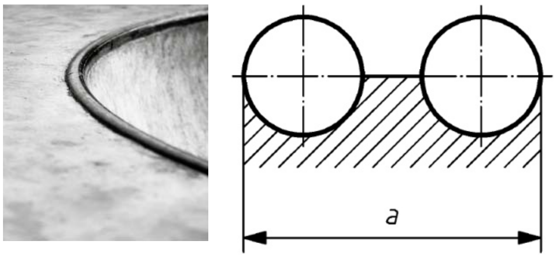
Some general principles are that all external accessible **edges** should be chamfered with a radius of at least **3 mm**. Also, the free fall height of the riding, grinding and rolling surface should not exceed **1.5m** [3]. The free-fall height is to be measured 1 m horizontally from the perimeter line of the supporting surface to the adjoining surface located at a lower level.

[3] *For exceptions, see relevant sub-clauses under the chapter 5.2 of BS EN 14974:2006.*

Later, some individual elements of the skate-boarding facilities are described. Due to the lack of technical information about skate-bowls, some data about variations of ramps has been collected, in order to understand the limitations of similar structures.

Coping

The coping is a metallic tube placed at the edge of a bowl or skateboard ramp for performing skateboarding tricks (Fig. 138). The **diameter** of copings shall be at least **40 mm**, while their ends should be sealed. The coping shall present a minimum projection of 3 mm forward and upward, a maximum projection of 12 mm forward and 30 mm upward (Fig. 139).



a mm
140 maximum
or 200 to 320
or 450 minimum

Fig. 139 Example of coping at the edge of a bowl (Left) and dimensions of copings arranged in parallel (Right - <u>Source:</u> BS EN 14974:2006, p.12).

Rail

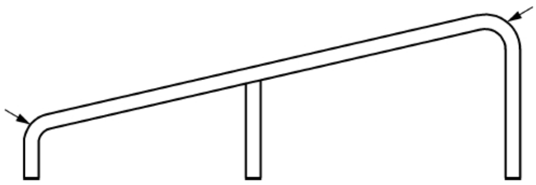


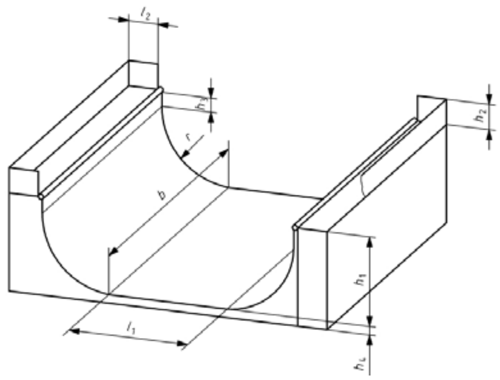
Fig. 140 Schematic drawing showing the outer radius or chamfer of 45° of a rail (<u>Source:</u> BS EN 14974:2006, p.15).

The rail is also used for acrobatics. The distance between the lower edge of the rail and the rolling surface shall be at least **20 cm** and the height of the rail shall not be greater than **100 cm**.

Finally, the ends of rails shall reach to the ground, while the outside radius or chamfer of **45**° should be at least **2 cm** (Fig. 140).

Half-pipe

The half-pipe is a structure that consists of two opposite transitions, connected by a horizontal surface (Fig. 141). Despite the fact that it is defined geometrically in a very rigid way, the minimum and maximum values of these structures can also be applied in the case of the bowl. The difference between the bowl and the half pipe is that the former has a curved surface which runs along its curved edges.

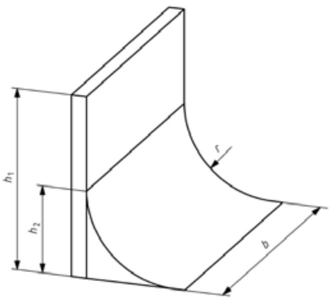


Description	h_1 mm	b mm	r mm	h_3 mm	h_2 mm	l_2 mm	l_1 mm	h_4 mm
Mini-Pipe	≤ 1 250	≥ 2 400	≥ 1 800 and ≥ h_1	No vert allowed	≥ 1 200	≥ 1 200	≥ r	≤ 600
	> 1 250 to 2 000	≥ 3 600						
	≥ 2 000 to 3 000	≥ 4 800						
Half-Pipe	≥ 2 500 ≤ 4 200	≥ 6 000	≥ 2 400 ≤ 3 600	≤ 600	≥ 1 200			
	≤ 4 200 to 5 000	≥ 7 200	≤ 4 500	maximum 1 000				

Fig. 141 Dimensions of a half-pipe from British Standards (BS EN 14974:2006, p.20)

<u>Wall ramp</u>

The wall ramp looks like a quarter pipe, but it has a vertical extension on the top. It has been included here because it is one of the tallest elements used in skateboarding, hence its limits can be used as a guideline for the vertical limit (Fig. 142).



Structure	Radius r mm	Width b mm	Height h_1 mm	Height h_2 mm
Wall ramp with transition	minimum 1 000 maximum 2 000	minimum 2 400	minimum 2 000	r ± 5 %
	> 2 000 to 3 000	minimum 3 600	≥ r	
Wall ramp with bank	—	minimum 2 400	minimum 1 500	maximum 1 500
		minimum 3 600		minimum 1 500 maximum 2 500

Fig. 142 Dimensions of a wall ramp (BS EN 14974:2006, p.18)

4.3.2 Design Methodology

The basis for the design of the skate bowl is the parametric definition of the surface by repulsion of the negative space. Yet, since the scale of this project is much larger than the size of a person, the motion data has been enlarged before applying it to the motion path. Also, the surface by repulsion results in a surface with very smooth transitions (Fig. 143), while in the case of the bowl, the top edge should have a very clear and sharp boundary to adjust the coping.

In order to agree with the previously mentioned parameters, the negative space is modified. The process followed is to cut the surface by repulsion with a horizontal plane, slightly lower than the highest z value. This results in the creation of a border, which is a closed curve geometrically (Fig. 143). This curve needs to be rebuilt with less control points for smoother results (Fig. 144). That forms the spine for the reconstruction of the negative space.

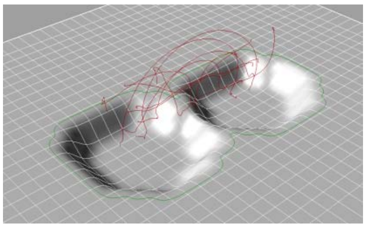


Fig. 143 The deformed surface sliced by a horizontal plane.

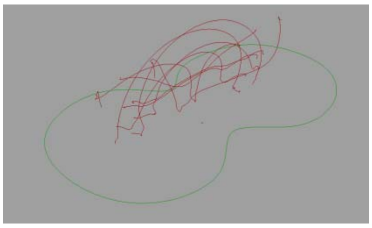


Fig. 144 The rebuilt intersection curve.

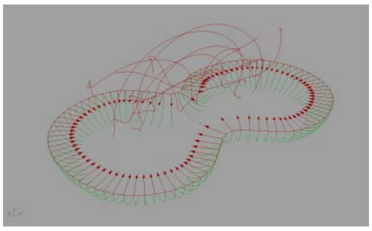


Fig. 145 Drawing multiple arcs around the perimetric curve.

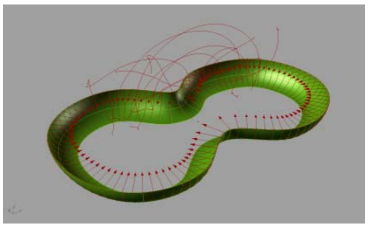


Fig. 146 Lofting the arcs to create a closed surface.

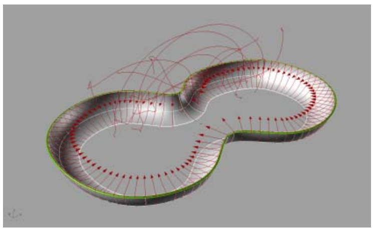


Fig. 147 The coping of the skate-bowl.

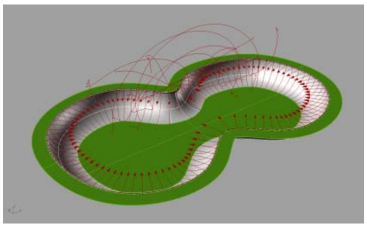


Fig. 148 The planar surfaces of the skate-bowl.

Afterwards, an arc is created to form the profile of the bowl. In order to specify the centre of the arc, a frame perpendicular to the curve is designed and a length, equal to the radius of the arc, is defined along the x axis of the frame. The radius of it reaches up to 2.5 m (maximum height limit of the wall ramp) and the angle interval is set to 90 degrees.

If the parametric curve is divided into equal segments, with perpendicular planes at the division points, then the arc can be repeated along the curve (Fig. 145). By lofting these arcs it is possible to produce the curved surface of the bowl (Fig. 146). Also, the bottom of the bowl is capped by a planar surface (Fig. 148).

For the design of the final bowl (Fig. 149) the previous definition with some transformation techniques are combined. The main idea is to compose a form deriving from the motion of two dancers. Thus, two paths are used along which motions are translated. The first path consists of two motions and the other of one. Since the scale of the project is rather extensive, the MoCap data is enlarged before being oriented.

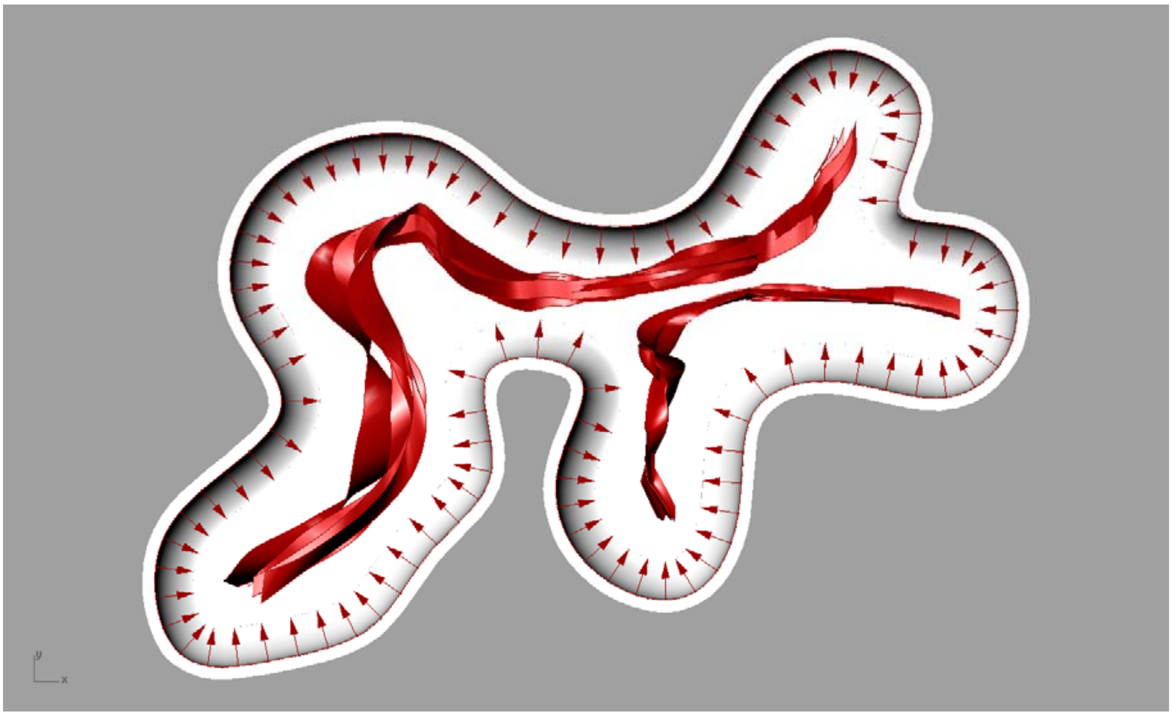


Fig. 149 The final skate-bowl as formed by combining two paths.

Minimum distance analysis for the transitional surface

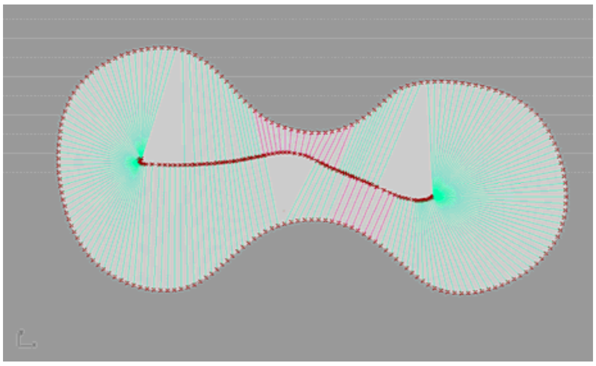


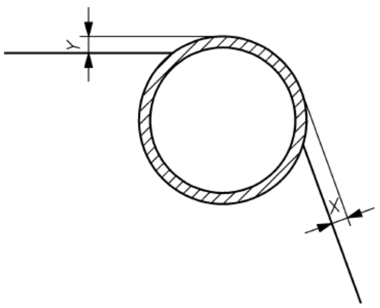
Fig. 150 Diagram indicating the invalid distances (pink) between the points of the perimeter and their closest points on the curve of the spine (C7).

One of the few restrictions of the skate-bowl derives from the limitations of the half-pipe, where the length of the transitional flat surface should be greater than or equal to the radius of the structure. In the case of the skate-bowl the transitional surface is the planar surface at the bottom. A reasonable question though is which distances should be measured and be compared with the radius of the arc.

One possible approach is to use the path of the movement projected on the transitional surface as a reference. Afterwards the perimeter's curve can be divided by a sufficient number of points and find their closest points on the path curve. Then, the distances between them can be compared with half of the radius of the arc and be coloured accordingly (Fig. 150). Thus, the user can have a direct visual feedback about the results of the chosen parameters and whether they need to be modified. However, since the points around the path are not distributed symmetrically, there is a chance that the invalid distances may not be a problem, because the distances at the opposite side may be sufficiently long, as in the middle of the shape in Fig. 150. Developing this check would be a subject for further exploration.

4.3.3 Materiality

Skateparks can be built either by concrete or wood. The former are usually outdoors because of the durability of the concrete, while the latter is preferred for indoor facilities. In both cases, there can be secondary elements made of wood and metal, such as ramps or rails.



$3 \text{ mm} \leq X \leq 12 \text{ mm}$

$3 \text{ mm} \leq Y \leq 30 \text{ mm}$

Fig. 151 Projection of the coping (Source: BS EN 14974:2006, p.12).

The current skate-bowl is designed as a concrete bowl with a metallic pipe forming the coping of the perimeter. The position of the coping in relation to the horizontal and inclined surface is indicated in Figure 151. The slider that defines the radius of the pipe is set within the allowed limits. Finally, a planar surface made of concrete is placed around the coping and its width can be also modified by sliders.

4.3.4 Digital Fabrication

Since there are no specifications about concrete bowls in British or European Standards, constructed examples of skate-bowls have been investigated, to provide information about their fabrication techniques. Digital fabrication can be partly used for the construction of a concrete bowl, combined with traditional techniques.

Fig. 152 Concrete bowl built in Flensburg, Germany.

Fig. 153 Construction of the 'Venice Beach Skatepark'.

Firstly, the coping forms the backbone of the structure (Fig. 152). Its fabrication can be achieved with a NC controlled pipe bending machine. The information needed can be easily extracted from Rhino by transforming the spline of the coping into arcs, which is the geometry that the machine can recognise.

For the construction of the concrete bowl, a wooden frame could be constructed, that would afterwards be covered with a layer of concrete (Fig. 153). The wooden frame may consist of the profiles of the arcs and horizontal connections that can be extracted from the parametric model, laser-cut and be assembled on site (Fig. 155). Power floated concrete is usually preferred for the coverage of the surface. Moreover, the area of the concrete surfaces can also derive from the parametric model, in order to estimate the quantity of concrete needed (Fig. 154).

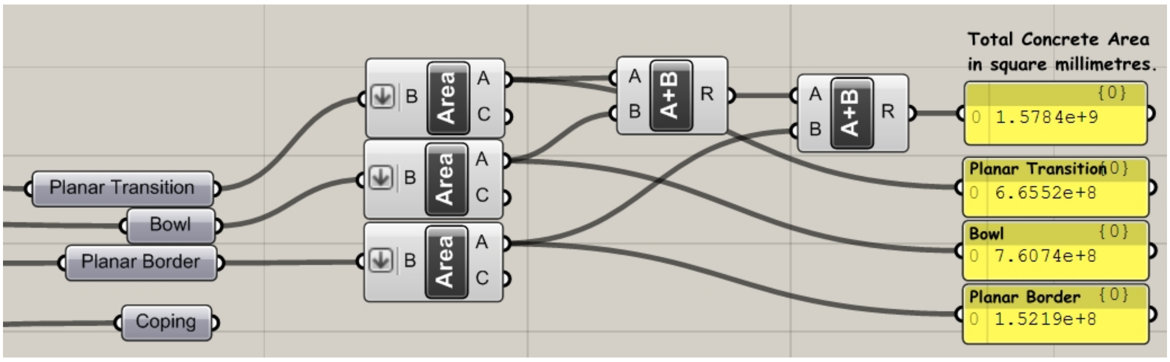


Fig. 154 Calculation of the area of all concrete elements.

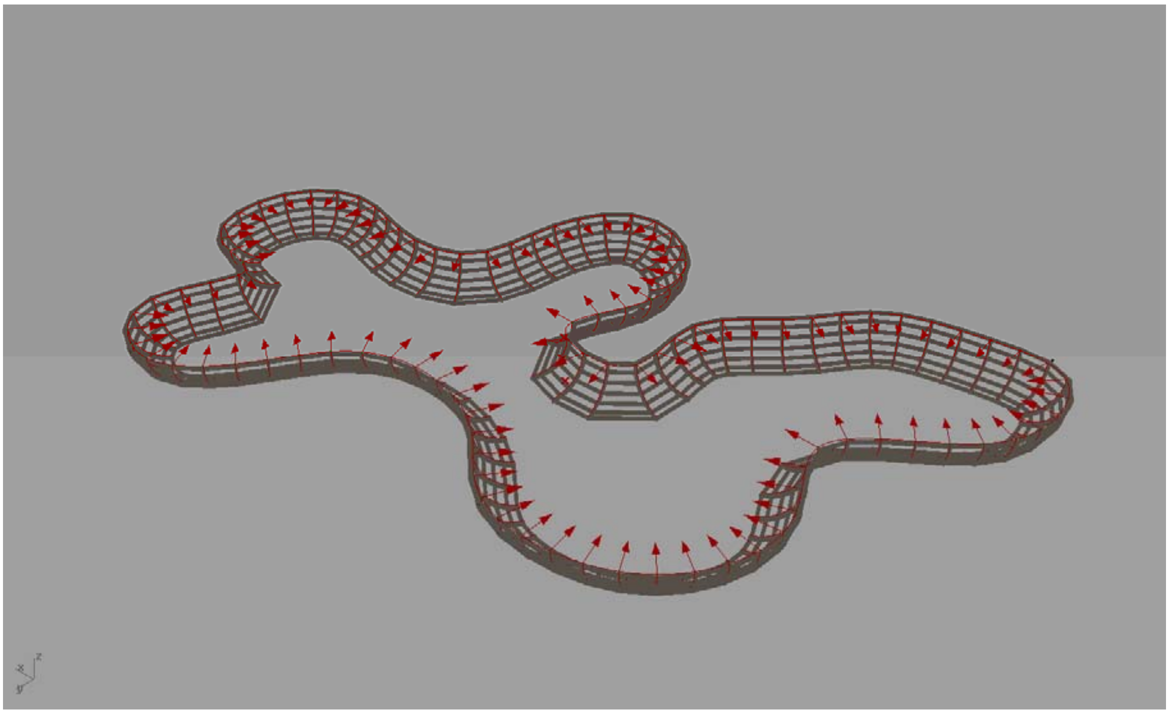


Fig. 155 Wooden frame for the construction of the concrete bowl.

4.3.5 Discussion

The parametric definition of the skate-bowl offered the chance to explore the negative space of movement. Moreover, the case of producing 'choreographic' space from two performers (two individual paths) has been examined, and this space has been modified according to the requirements of this particular case-study. Fabrication techniques have been also incorporated in the parametric definition, demonstrating the considerable possibilities of parametric modelling in design.

Generally, producing the parametric model for the skate-bowl has been a straightforward process with some rather precise geometrical parameters, but also adequate freedom regarding its shape. Yet, the functional requirements led inevitably to modifications of the surface by repulsion, which partially altered the original geometry.

Subjects that could be further explored regarding the negative space is the deformation of the surface on variable heights, as the current definition translates a group of points to the same height. This would add a supplementary sculptural quality to the form of negative space and would reflect more effectively the result of movement to its surrounding space.

5. CONCLUSIONS

5.1 Results

The current dissertation has provided a research with various points of view regarding the analysis and visualisation of dance, and also the connection of it with architecture through parametric modelling. Despite the popularity of the subject, none of the previously existing research explores the subject from the perspective of motion's elements and spatial qualities and their equivalents in architecture. Yet through this research the connection between architecture and dance is no longer notional, but also practical.

In terms of visualisation, dance can be represented in a symbolic way (dance notation), video recorded, animated (inverse kinematics and motion capture) or in a combination of these. 'Synchronous Objects' suggests approaches and techniques that take visualisation of dance one step further, indicating the connection of dance with other disciplines. This analysis paved the way for developing a connection between architecture and dance. Motion Capture Data constituted the raw material for this attempt.

The creation of a 'library' of movements from MoCap offered the chance to understand some of the features of movement that led to classification of them into five 'actions'. The visualisation of 'actions' indicated the similarities, differences and spatial characteristics of movement, as well as the frozen presence of time. Time is incorporated into the parametric model as a hidden and underlying attribute that defines the sequence of shapes. Thus, stillness and movements occurring at the same place result in clusters of points that need to be treated differently to a movement developing in space. These kinds of movements are unsuitable to be translated along a path and can only be treated as fixed entities, unless their excessive deformation is the intention of the designer.

Understanding and forming transformation tools for the frozen dance forms has been the key for the application of them to the design project. However, the generic nature of transformations renders their possibility to be applied in other cases as well. Translation, orientation, scale, simplifying and merging of dance motions have been the techniques explored so far. Experimenting with other affine transformations and deformation processes could be an objective for future research.

The case-studies are based on examples coming one from positive space and a second from the negative space of dance movement. Although both comprise of abstract forms, the positive space structure has been simplified less, compared to the negative's space structure. So the result of the former maintains more of the qualities of dance, while the latter, after continuous elaboration, has lost its dance origin. Thus, the positive space's geometry is 'read' better as dance form than the negative space, which is rather abstract.

Dealing with parameters of functionality generated methods for elaborating dance forms to respond to the requirements of a specific project. The specifications of the project led to major or minor alterations of the original geometry. Also, restrictions have been included into the model as minimum and maximum values in the sliders. Supplementary design elements (protective surface, footing, etc.) have been incorporated to the general parametric model and related to the geometry of dance. Finally, another group of definitions performed analysis that indicated invalid parts of the structure that needed to be changed.

The suggested construction details have been more indicative, rather than the optimal solutions for the construction of such structures. However, they present very clearly the significant contribution of parametric modelling into the fabrication processes. The interconnected data offer the opportunity to change their parameters and automatically update all the linked objects. This possibility constitutes a radical development in the design process, compared with the traditional practices of the past. Instead of a linear sequence of actions, a parametric model can be modified easily, without losing the interrelations of its elements, optimising significantly the duration of design the variations of solutions.

In short, this research managed to span the disciplines of architecture and dance regarding space, time and form, through parametric modelling. The grammar and the principles of dance formed the basis for the development of innovative design methods and new forms of expression, but mostly it enriched our understanding of space through motion and dance.

5.2 Recommendations for further research

Dance has a very broad and sophisticated vocabulary of movements. This vocabulary could not be explored sufficiently in this research in the desired detail, because of lack of Motion Capture representing dance movements in a systematic way. Moreover, the performers of the MoCap used were non-professional dancers or not dancers at all. Therefore, they could not push the limits of the body's potential in the same way dancers do, nor execute dance movement with professional precision. Consequently, expanding the 'library' of movements with MoCaps recorded by professional dancers would broaden the design possibilities of dance and offer more sophisticated results regarding form.

Another aspect of dance that would be interesting to be explored is the possibilities of three-dimensional forms produced by multiple dancers and configurations of movements. Exploring the patterns of those configurations in a more precise and systematic way is worth examining.

Fig. 156 Hinge joints.

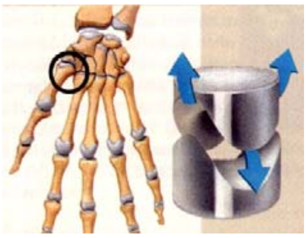


Fig. 157 Saddle joints.

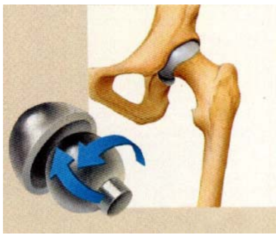


Fig. 158 Ball & socket joints.

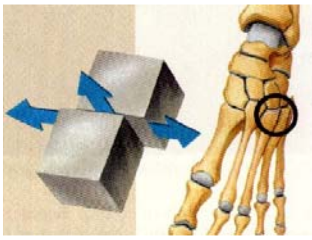


Fig. 159 Gliding joints.

The structure of the body has already been interpreted as a constructive structure. An interesting question would be whether the dance form could use modular elements, the same way the body uses modular joints. How could a hinge joint or a socket joint acquire an equivalent joint at the frozen dance forms? To what extent could this be possible? Finally is there a way to represent the dynamics of movement and find qualities in architectural forms that could be equivalent to the qualities of movement? All these issues constitute challenges that could be explored and analysed as a sequence of this research.

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APPENDICES

APPENDIX_A | Correspondence between the markers and the parts of the body

MARKER	LABEL	SIDE	EXPLANATION
1	RTOE	Right	Toe
2	RMT5	Right	Metatarsal
3	RHEE	Right	Heel
4	RANK	Right	Ankle
5	RSHN	Right	Shin
6	RKNE	Right	Knee
7	RTHI	Right	Thigh
8	RFWT	Right	Hip
9	RWRA	Right	Wrist A
10	RFIN	Right	Finger
11	RWRB	Right	Wrist B
12	RFRM	Right	Forearm
13	RELB	Right	Elbow
14	RUPA	Right	Upper Arm
15	RSHO	Right	Shoulder
16	RFHD	Right	Front Head
17	LFHD	Left	Front Head
18	LSHO	Left	Shoulder
19	LUPA	Left	Upper Arm
20	LELB	Left	Elbow
21	LFRM	Left	Forearm
22	LWRB	Left	Wrist B
23	LFIN	Left	Finger
24	LWRA	Left	Wrist A
25	LFWT	Left	Hip
26	LTHI	Left	Thigh
27	LKNE	Left	Knee
28	LSHN	Left	Shin
29	LANK	Left	Ankle
30	LHEE	Left	Heel
31	LMT5	Left	Metatarsal
32	LTOE	Left	Toe
33	LBWT	Left	Back Waist
34	RBWT	Right	Back Waist
35	RBAC	Right	Shoulder Blade
36	RBHD	Right	Back Head
37	LBHD	Left	Back Head
38	T10	Middle	T10
39	C7	Middle	C7
40	CLAV	Middle	Front Upper Chest
41	STRN	Middle	Sternum

Right Markers
Left Markers
Middle Markers
Selected Right Markers
Selected Left Markers

APPENDIX_B | Movements Catalogue

1. Individual Movements

1.1 Travelling

1.1_ walking

1.2_ running

1.2 Turning

2.1_ cartwheel 1

2.2_ cartwheel 2

2.3_ twist on the floor

2.4_ back flip

2.5_ wide leg roll

2.6_ front hand flip

1.3 Elevation

3.1_ hop (take off from 1foot, land on the same foot)

3.2_ grand jete (take off from 1foot, land on the other foot)

3.3_ run, leap (take off from 1foot, land on the other foot)

3.4_ forward jump (take off from 2 feet, land on the 2 feet)

1.4 Falling

4.1_ backward summersault

4.2_ rug pull fall

4.3_ falling and rolling

4.4_ get up from ground, laying on right side

4.5_ get up from ground, laying on left side

1.5 Isolation

5.1_ twist around the spine

5.2_ twist arms

5.3_ side twists

5.4_ bend over

5.5_ bend diagonally

2. Sequences of Movements

Seq.1_ small jetes, attitude/arabesque, shifted-axis pirouette, turn

Seq.2_ cartwheels

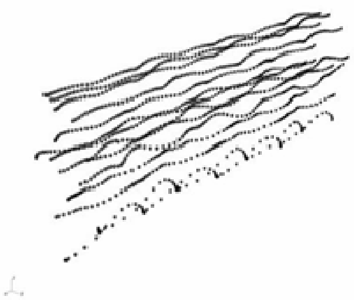
Seq.3_ twists lying on the back

Seq.4_ forward jumps (take off from 2 feet, land on the 2 feet)

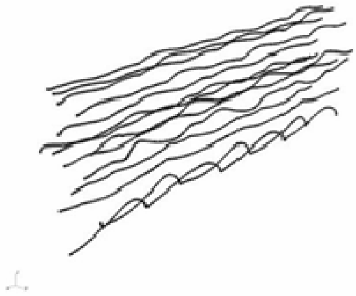
Seq.5_ alternating jumping jacks (take off from 2 feet, land on the 2 feet)

1.1_ walking

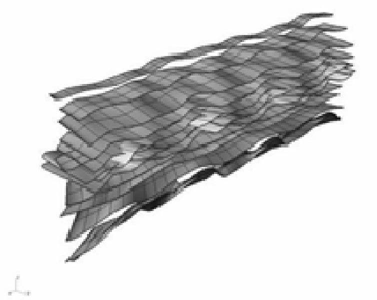
// positive space //



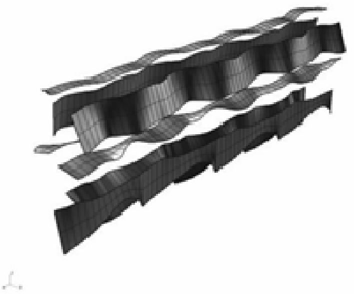
>> *Points*



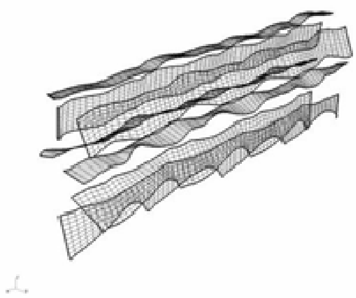
>> *Lines*



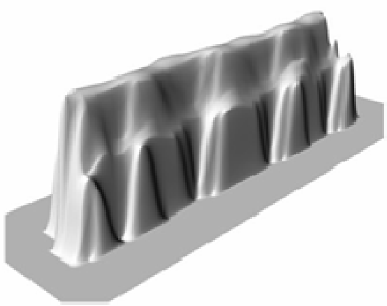
>> *Surfaces by symmetrical limbs*



>> *Surfaces by adjacent joints*

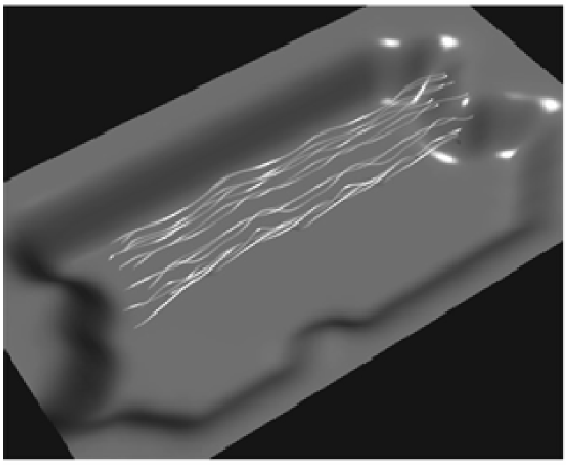


>> *Grids*

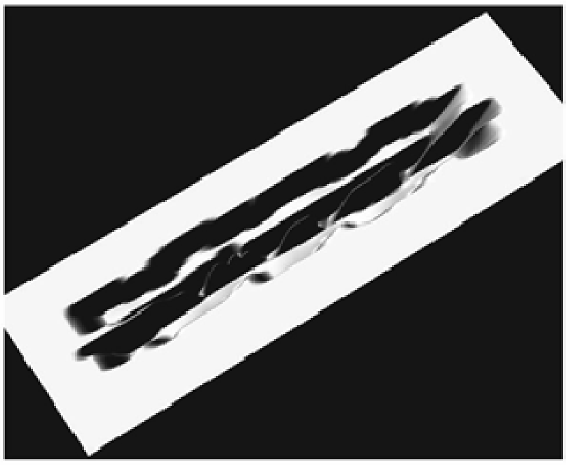


>> *Volume by draping*

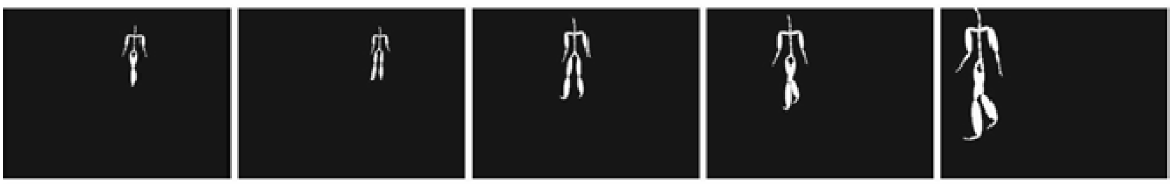
// negative space //



>> *Surface by repulse*



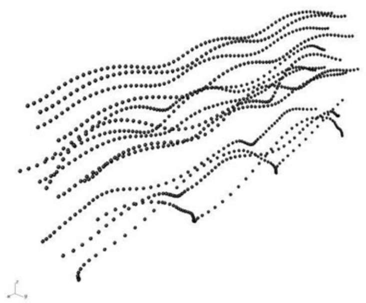
>> *Volume by reverse draping*



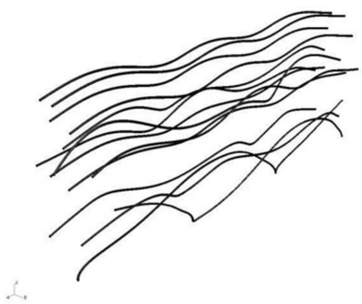
>> *Animation frames*

1.2_ running

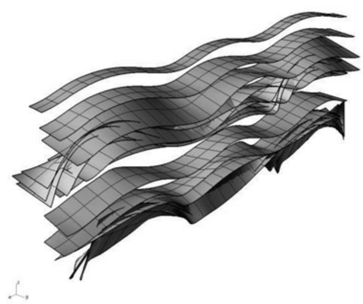
// positive space //



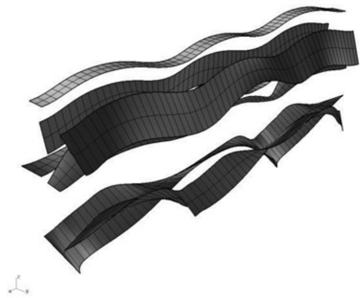
>> Points



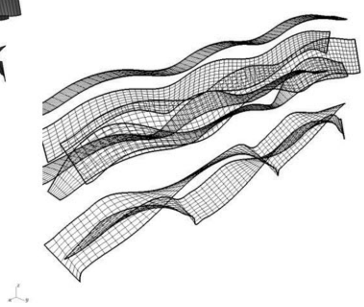
>> Lines



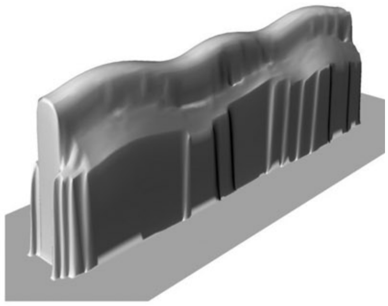
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

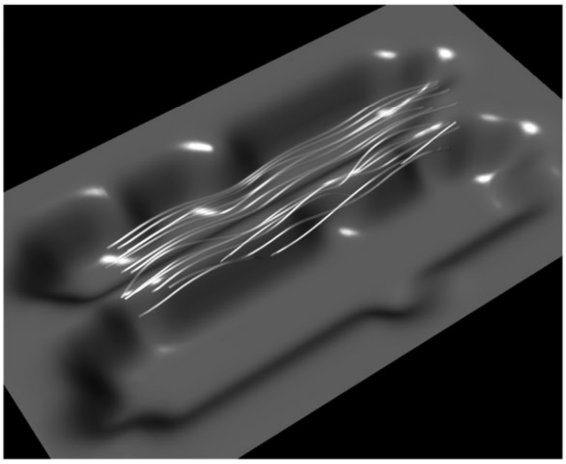


>> Grids

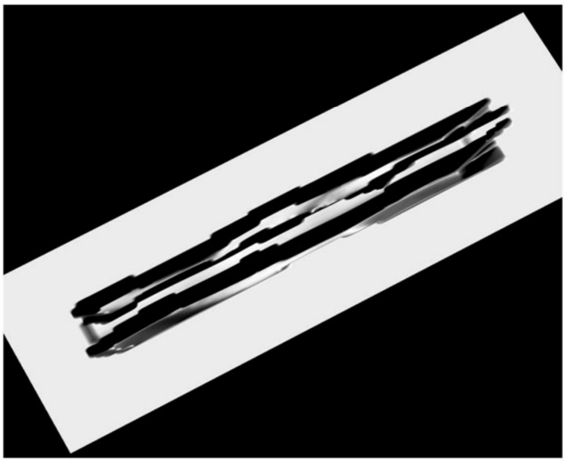


>> Volume by draping

// negative space //



>> Surface by repulse

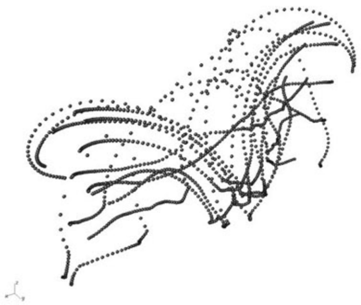


>> Volume by reverse draping

>> Animation frames

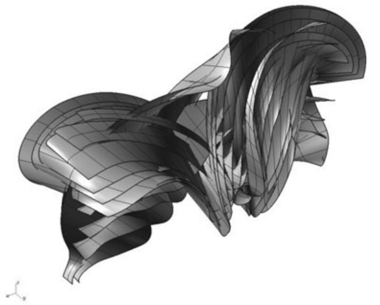
2.1_ cartwheel 1

// positive space //



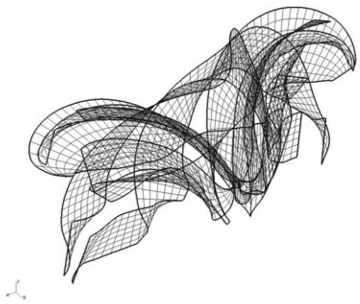
>> Points

>> Lines

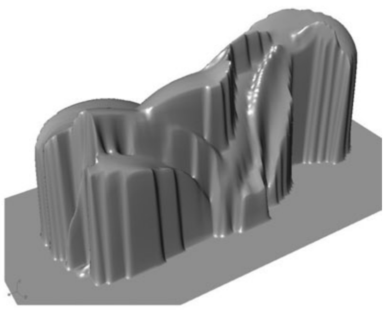


>> Surfaces by symmetrical limbs

>> Surfaces by adjacent joints

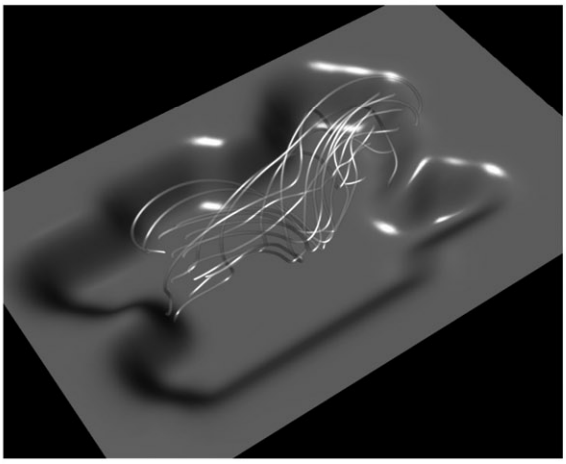


>> Grids



>> Volume by draping

// negative space //



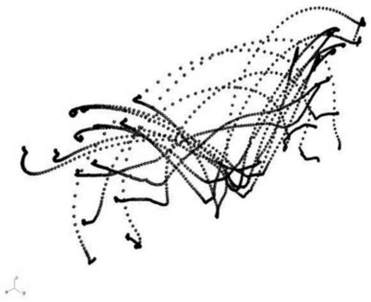
>> Surface by repulse

>> Volume by reverse draping

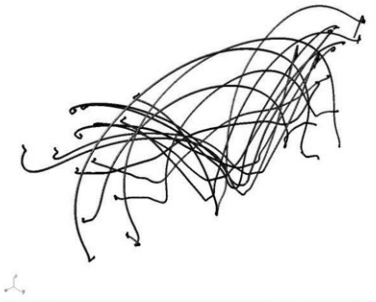
>> Animation frames

2.2_ cartwheel 2

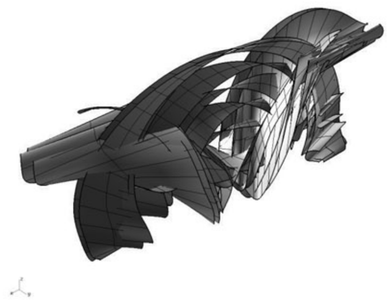
// positive space //



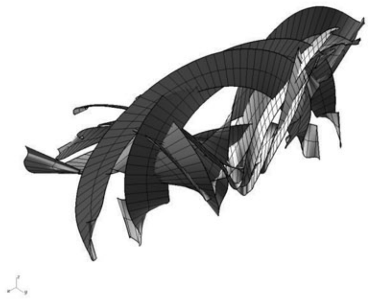
>> Points



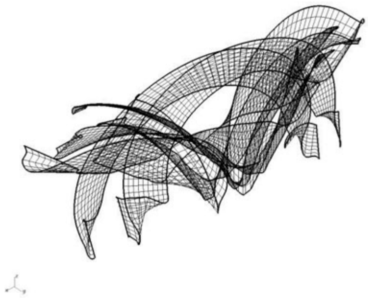
>> Lines



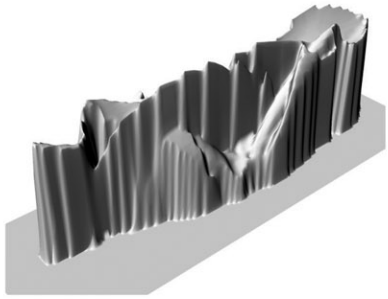
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

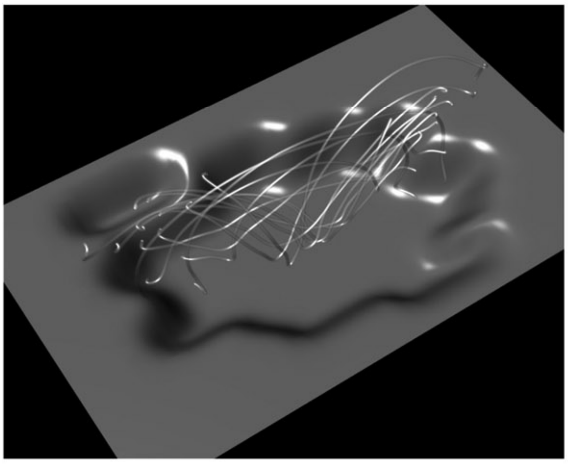


>> Grids

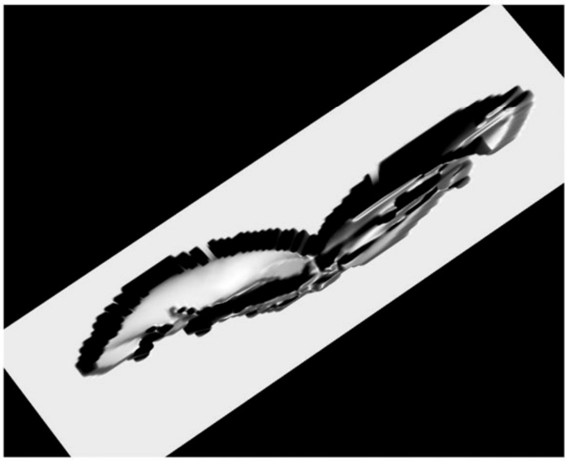


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

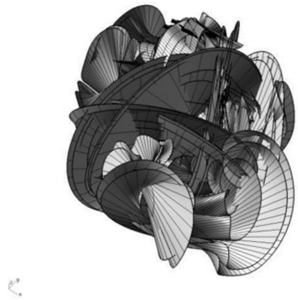
>> Animation frames

2.3_ twist on the floor

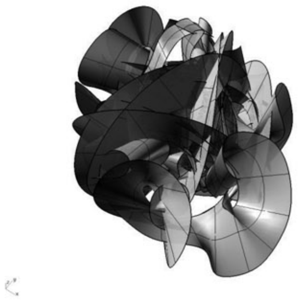
// positive space //

>> Points

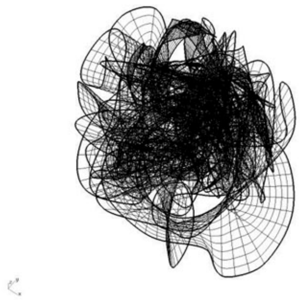
>> Lines



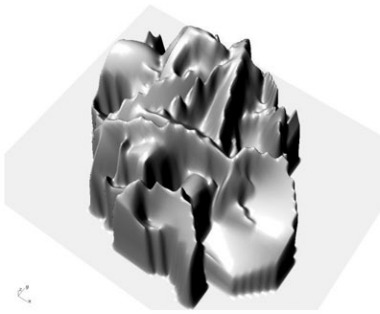
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

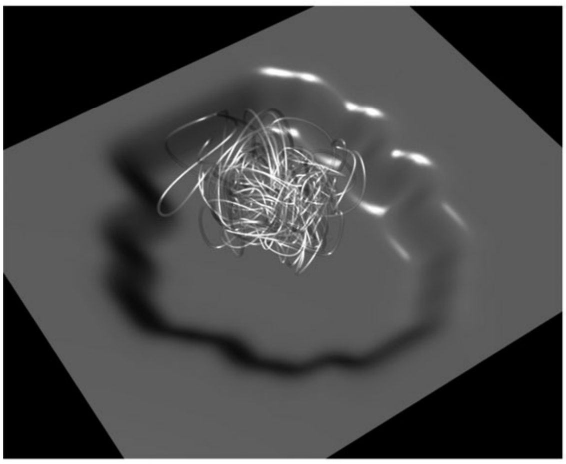


>> Grids

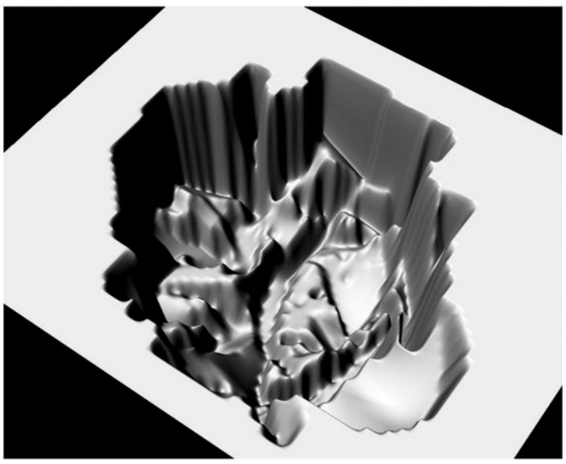


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

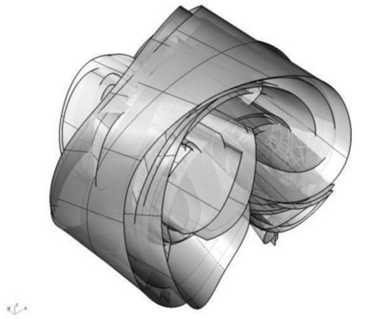
>> Animation frames

2.4_ back flip

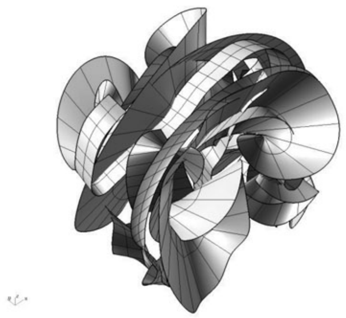
// positive space //

>> Points

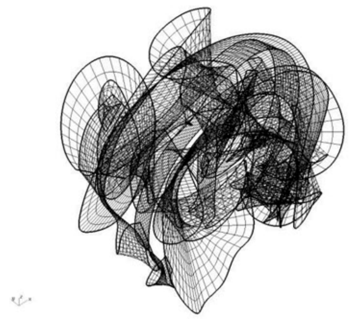
>> Lines



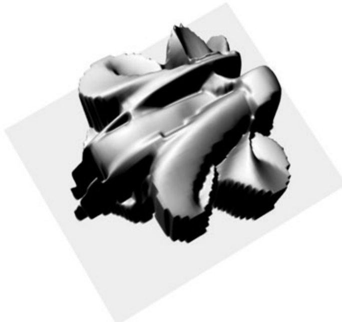
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

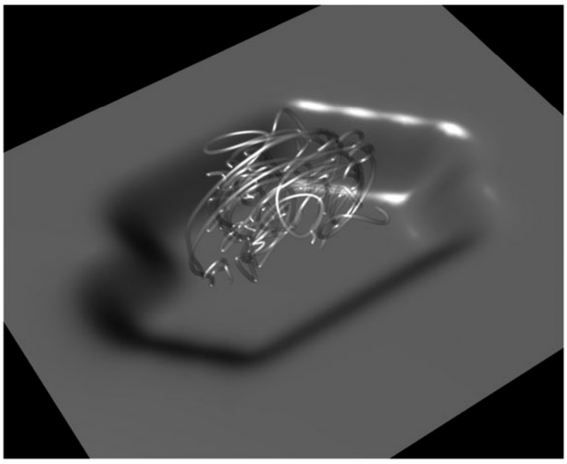


>> Grids



>> Volume by draping

// negative space //



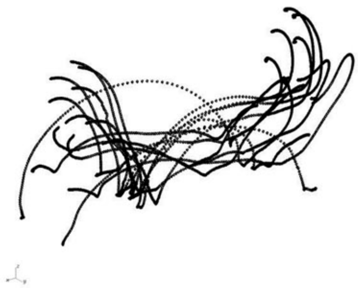
>> Surfaces by repulse

>> Volume by reverse draping

>> Animation frames

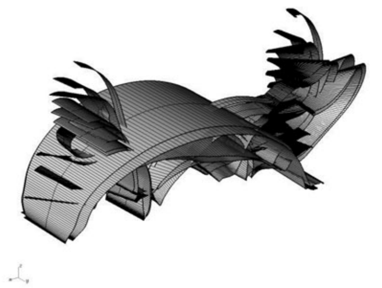
2.5_ wide leg roll

// positive space //

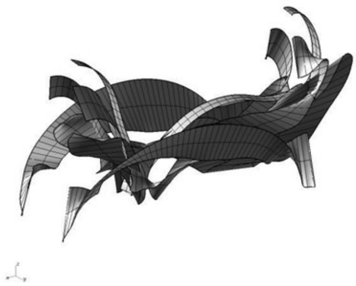


>> Points

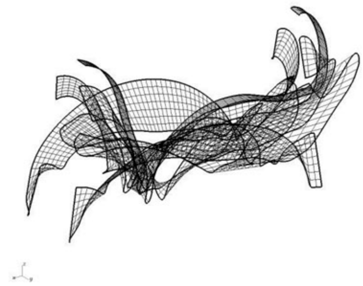
>> Lines



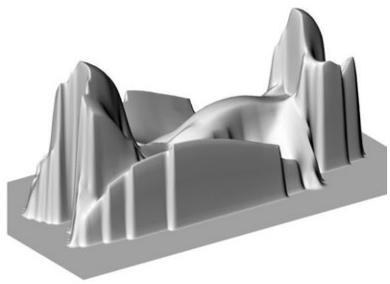
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

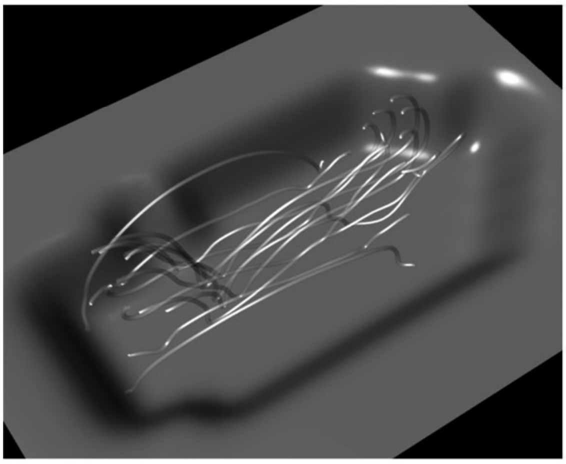


>> Grids

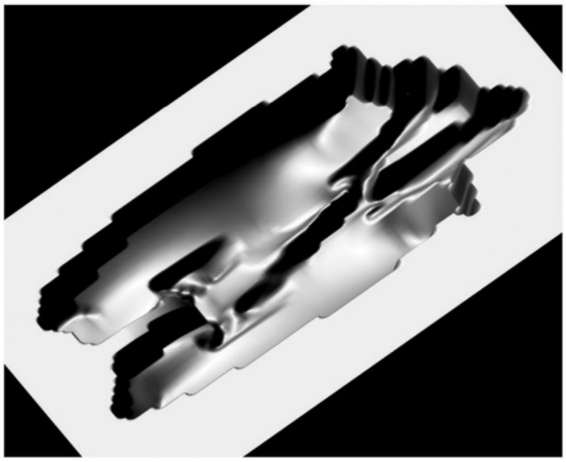


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

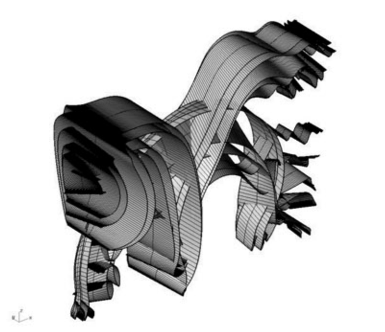
>> Animation frames

2.6_ front hand flip

// positive space //

>> Points

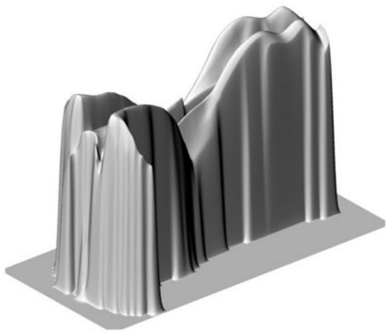
>> Lines



>> Surfaces by symmetrical limbs

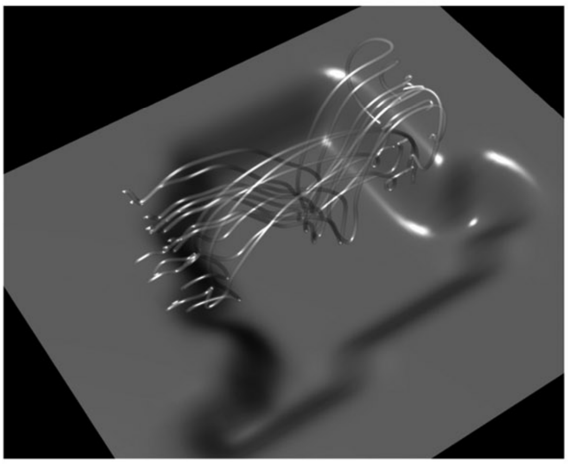
>> Surfaces by adjacent joints

>> Grids

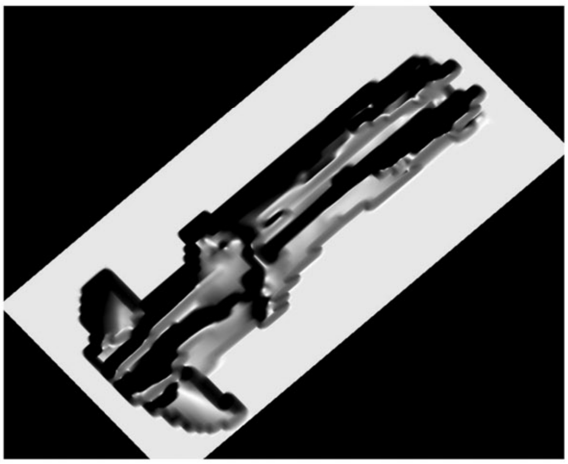


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

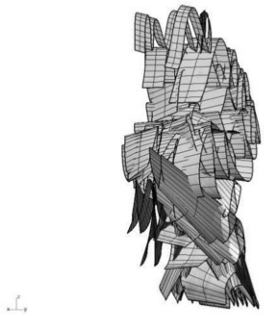
>> Animation frames

3.1_ hop

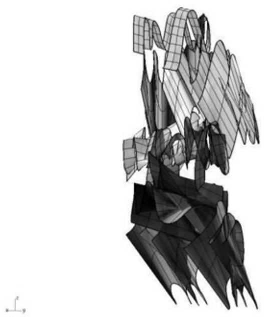
// positive space //

>> Points

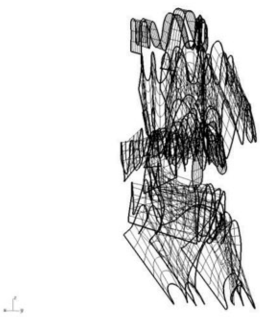
>> Lines



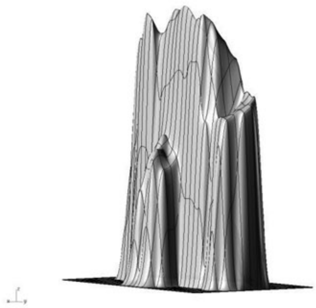
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

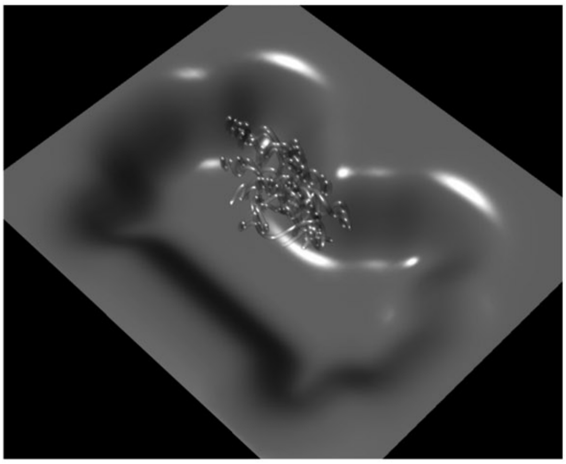


>> Grids

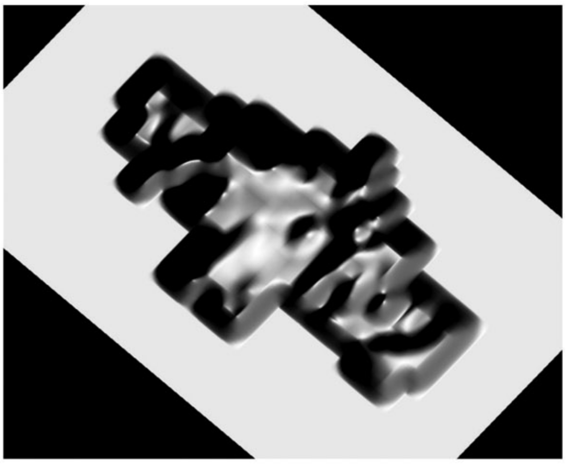


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

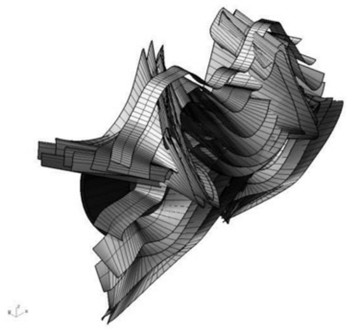
>> Animation frames

3.2_ grand jete

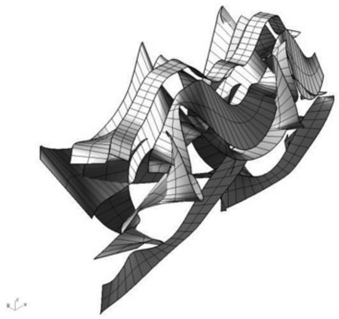
// positive space //

>> Points

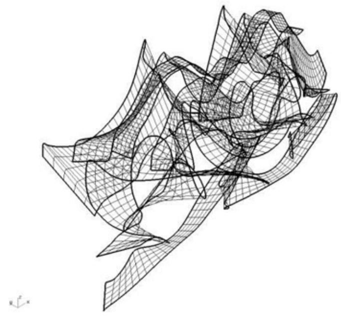
>> Lines



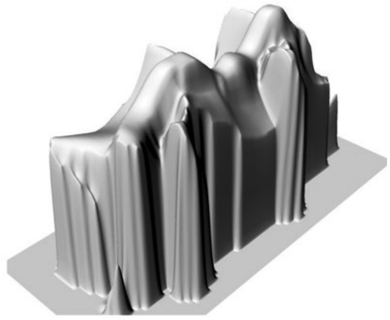
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

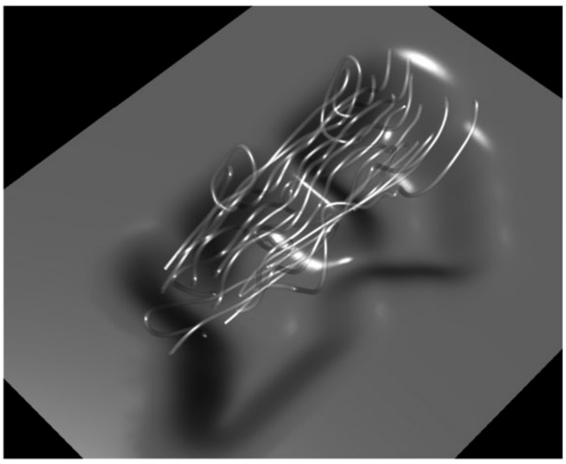


>> Grids

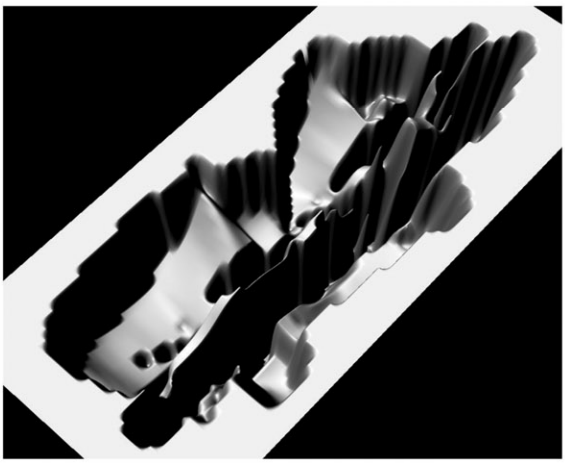


>> Volume by draping

// negative space //



>> Surfaces by repulse

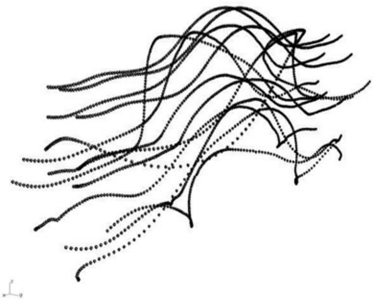


>> Volume by reverse draping

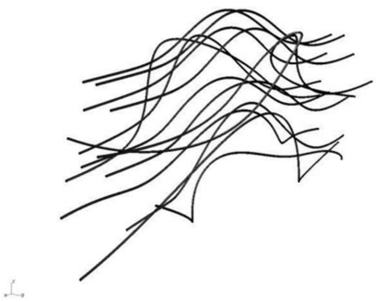
>> Animation frames

3.3_ run, leap

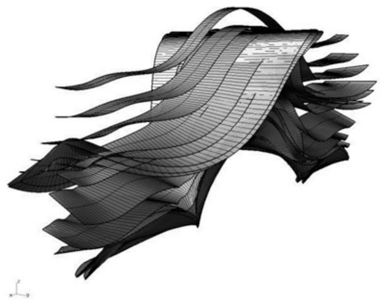
// positive space //



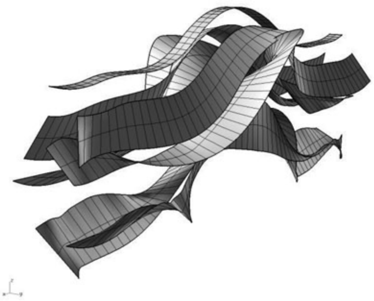
>> Points



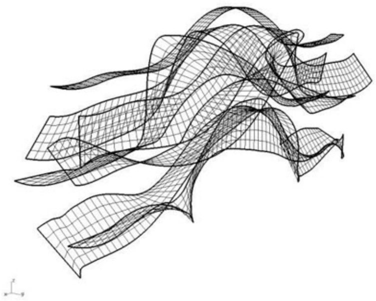
>> Lines



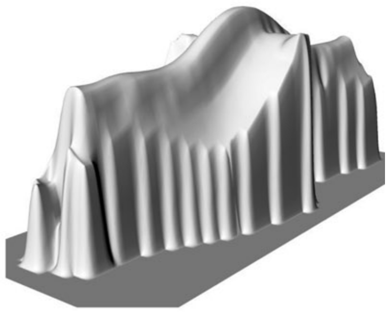
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

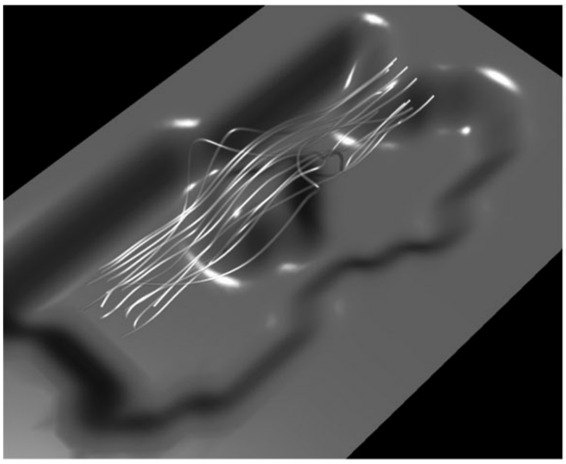


>> Grids



>> Volume by draping

// negative space //



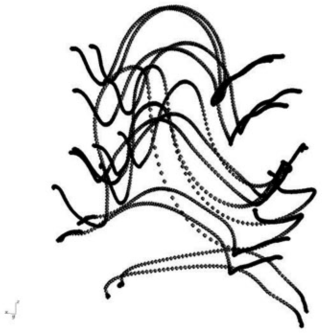
>> Surfaces by repulse

>> Volume by reverse draping

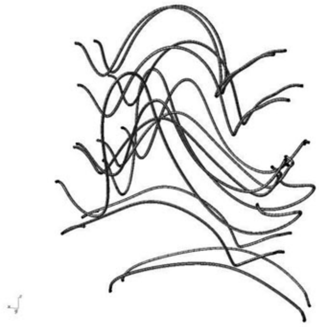
>> Animation frames

3.4_ forward jump

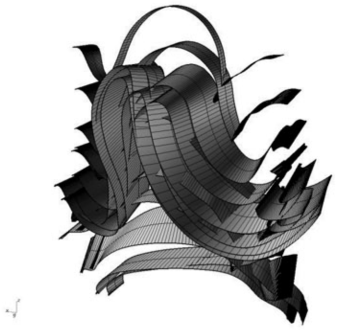
// positive space //



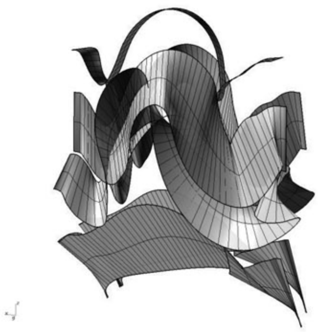
>> Points



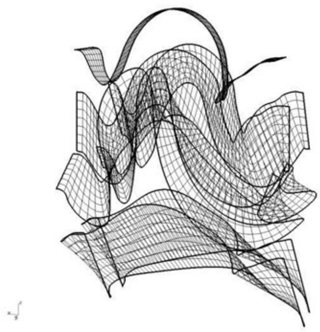
>> Lines



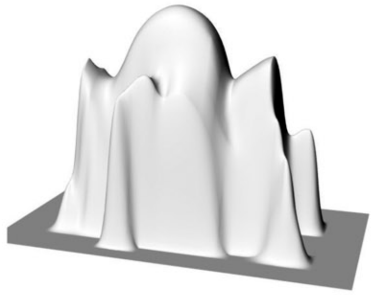
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

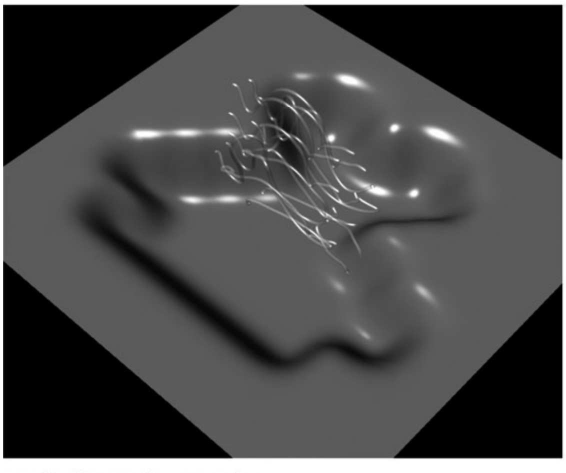


>> Grids

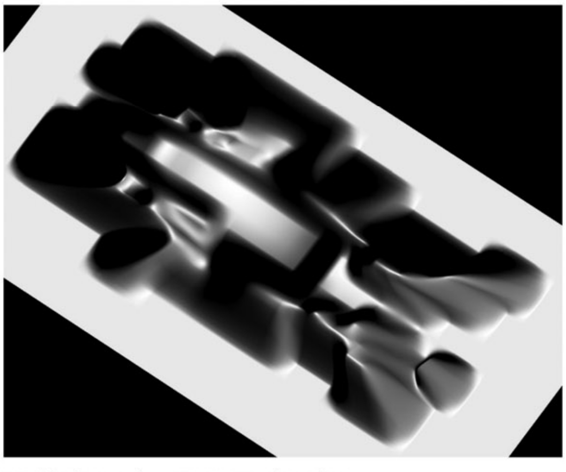


>> Volume by draping

// negative space //



>> Surfaces by repulse

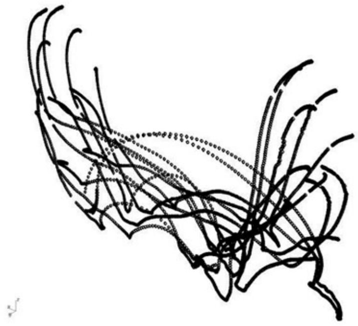


>> Volume by reverse draping

>> Animation frames

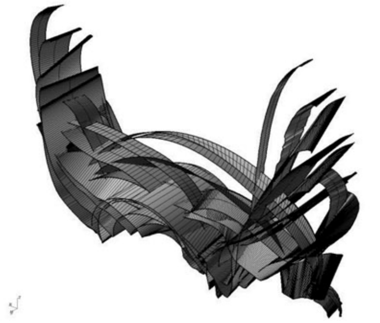
4.1_ backward summersault

// positive space //

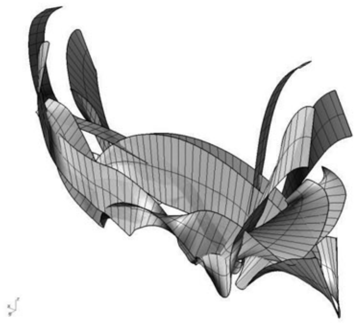


>> Points

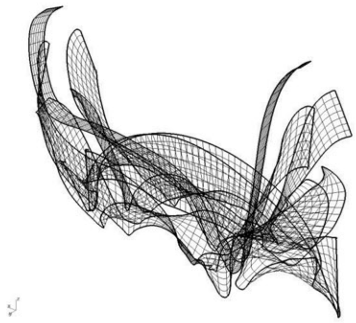
>> Lines



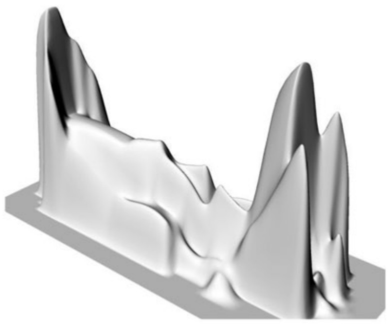
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

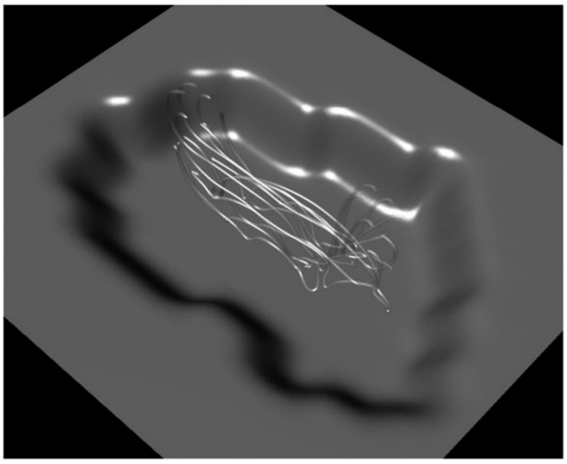


>> Grids

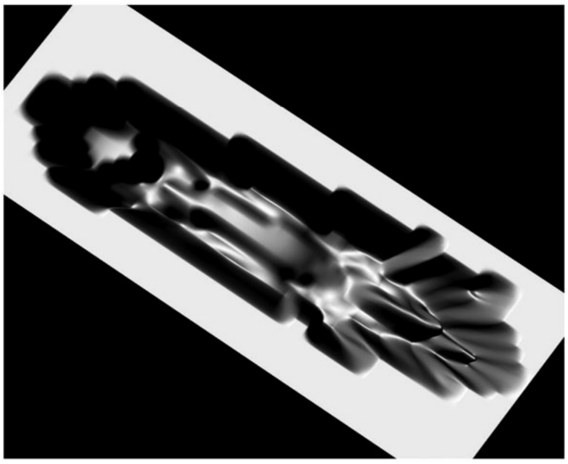


>> Volume by draping

// negative space //



>> Surfaces by repulse

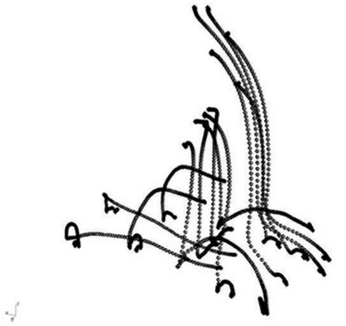


>> Volume by reverse draping

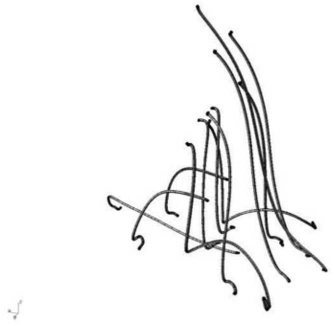
>> Animation frames

4.2_ rug pull fall

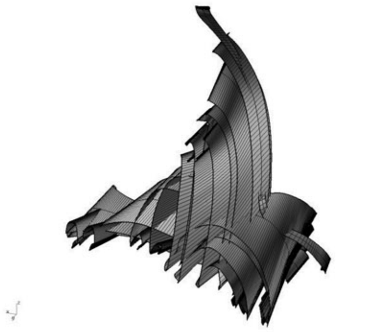
// positive space //



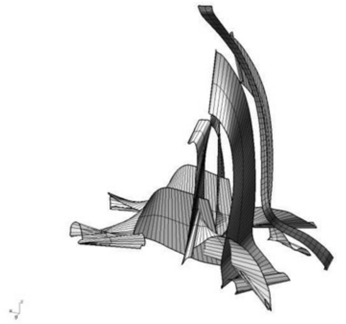
>> Points



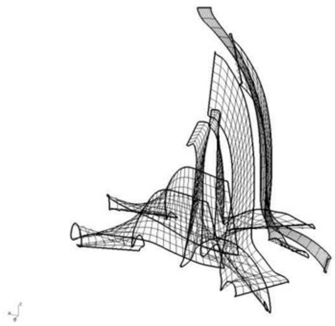
>> Lines



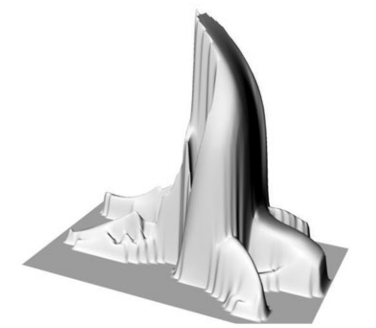
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

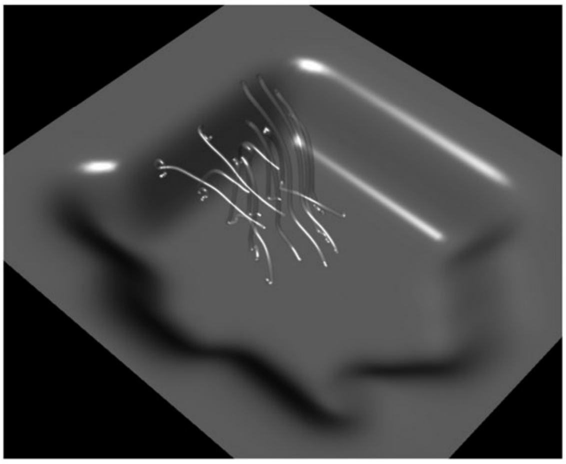


>> Grids

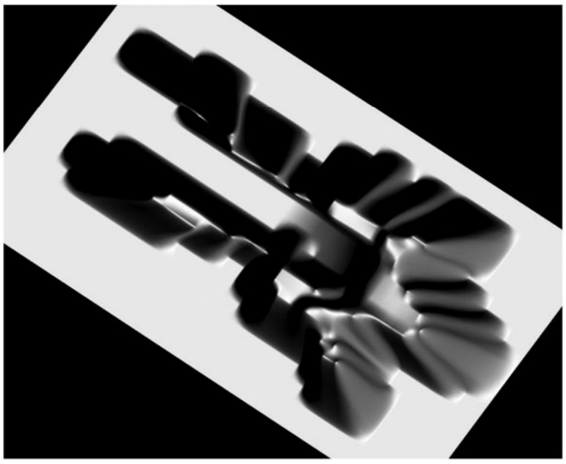


>> Volume by draping

// negative space //



>> Surfaces by repulse

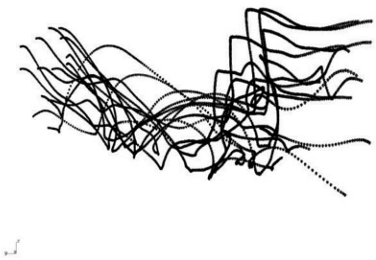


>> Volume by reverse draping

>> Animation frames

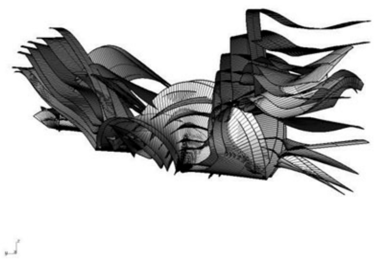
4.3_ falling and rolling

// positive space //

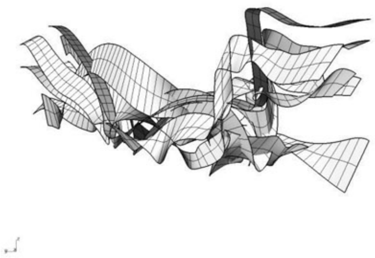


>> Points

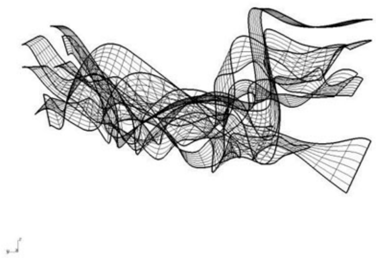
>> Lines



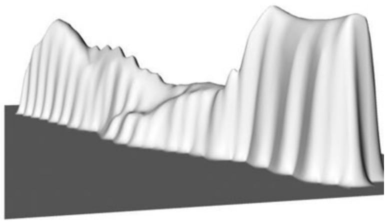
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

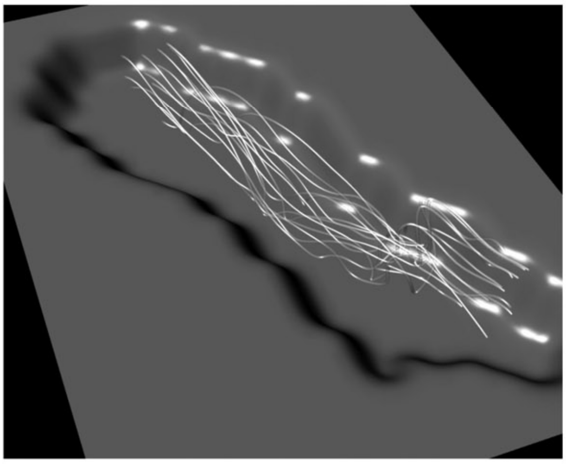


>> Grids

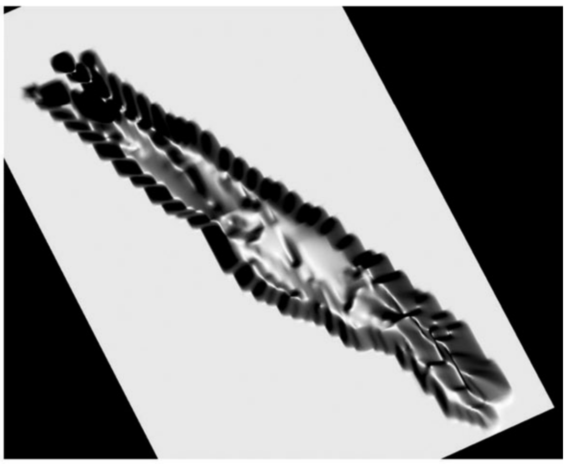


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

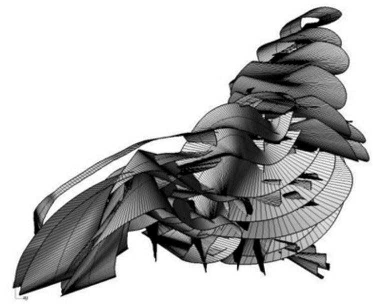
>> Animation frames

4.4_ get up from ground, laying on right side

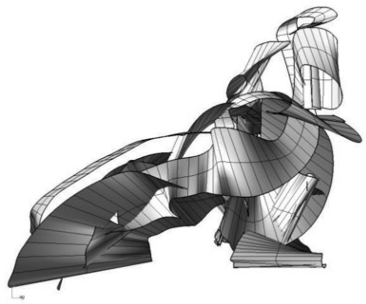
// positive space //

>> Points

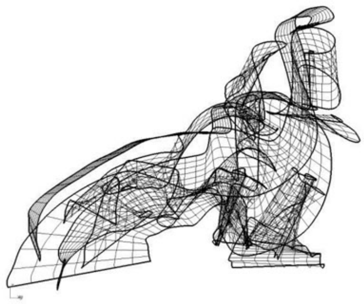
>> Lines



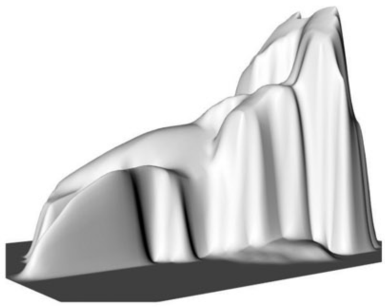
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

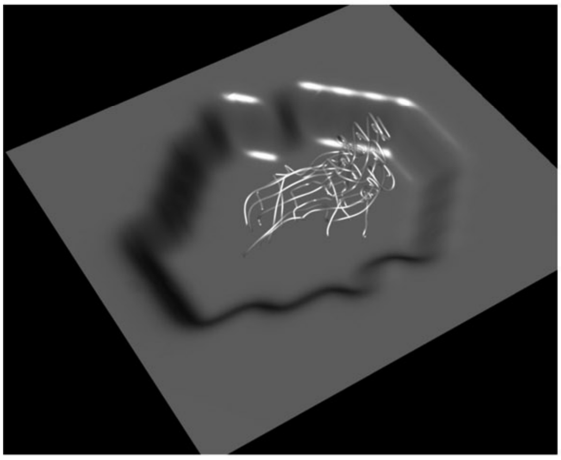


>> Grids

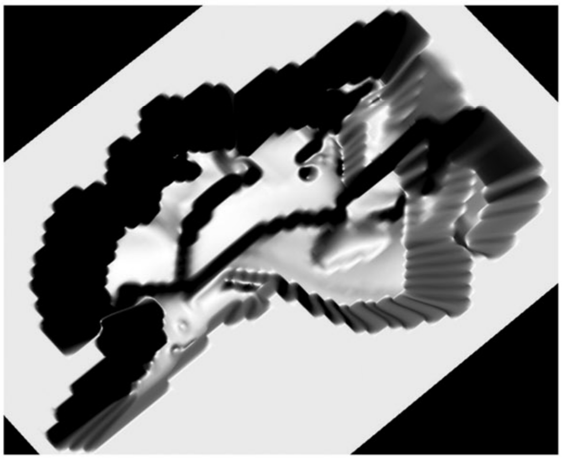


>> Volume by draping

// negative space //



>> Surfaces by repulse

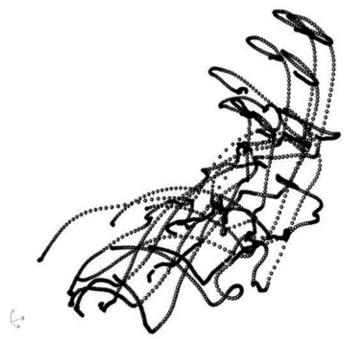


>> Volume by reverse draping

>> Animation frames

4.5_ get up from ground, laying on left side

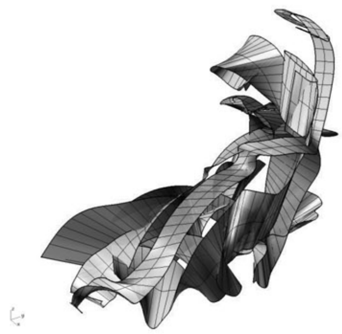
// positive space //



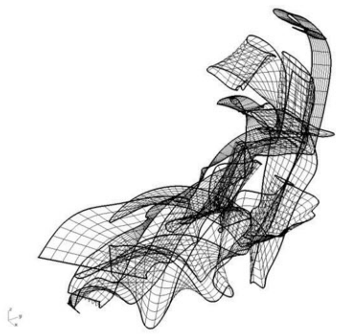
>> Points

>> Lines

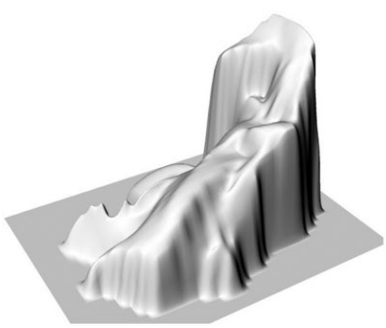
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

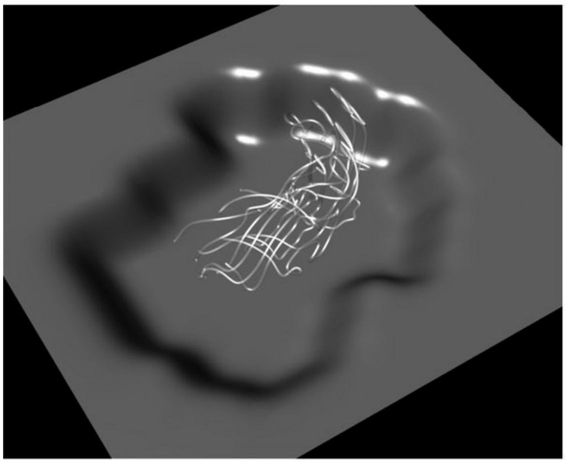


>> Grids

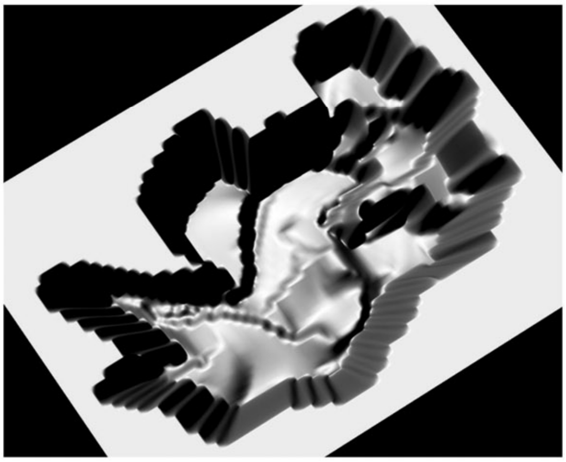


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

>> Animation frames

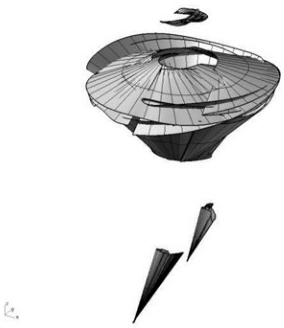
5.1 _ twist around the spine

// positive space //

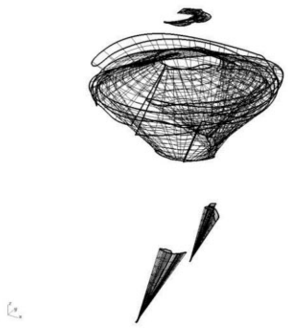
>> Points

>> Lines

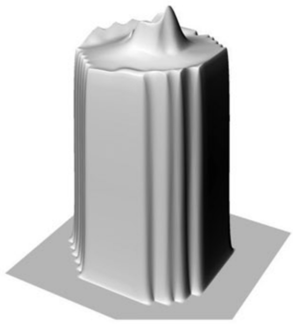
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

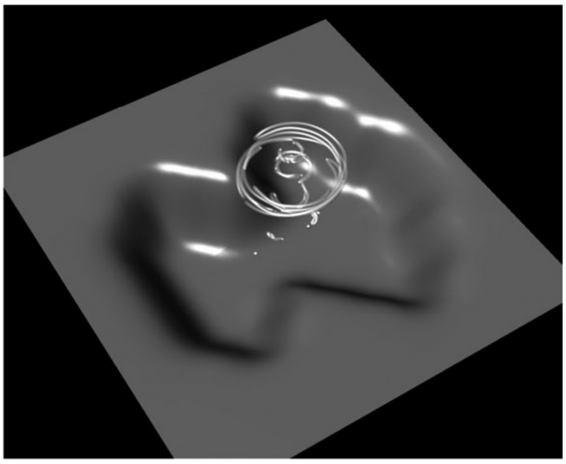


>> Grids

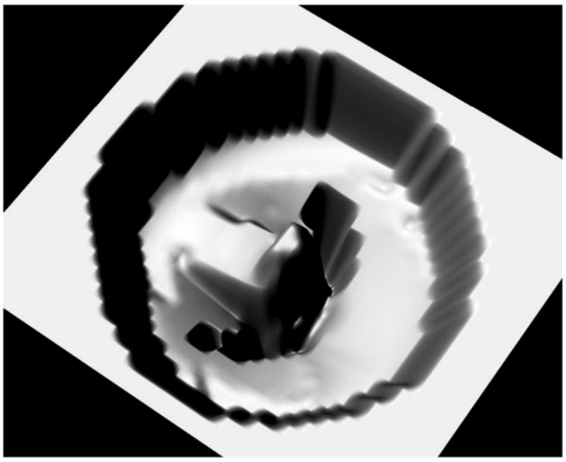


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

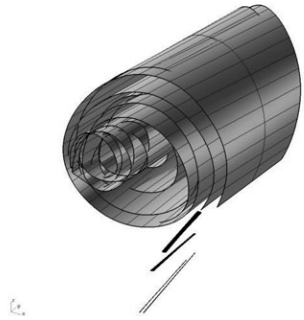
>> Animation frames

5.2_ twist arms

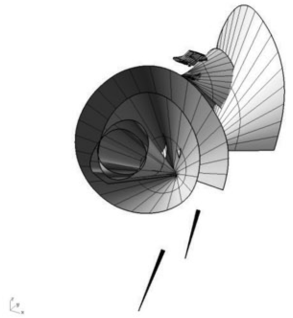
// positive space //

>> *Points*

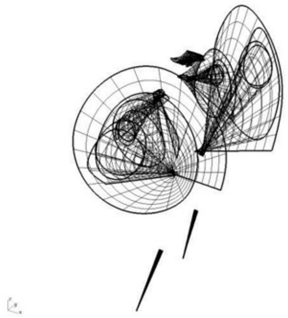
>> *Lines*



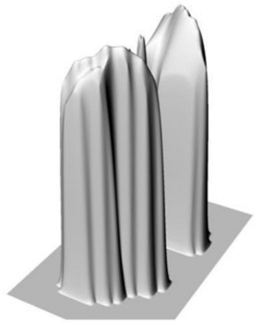
>> *Surfaces by symmetrical limbs*



>> *Surfaces by adjacent joints*

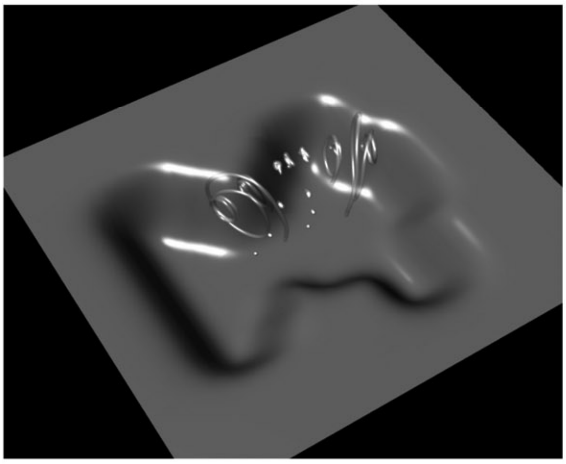


>> *Grids*

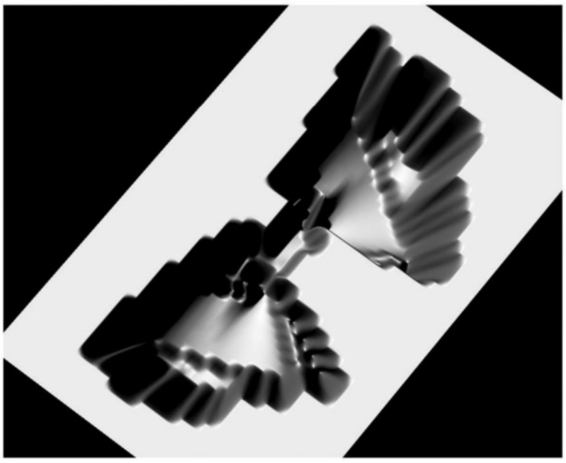


>> *Volume by draping*

// negative space //



>> *Surfaces by repulse*



>> *Volume by reverse draping*

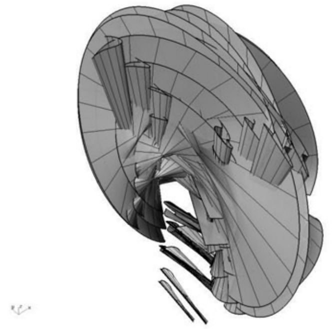
>> *Animation frames*

5.3_ side twists

// positive space //

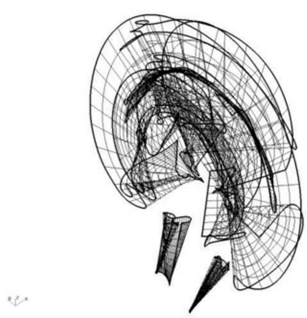
>> Points

>> Lines



>> Surfaces by symmetrical limbs

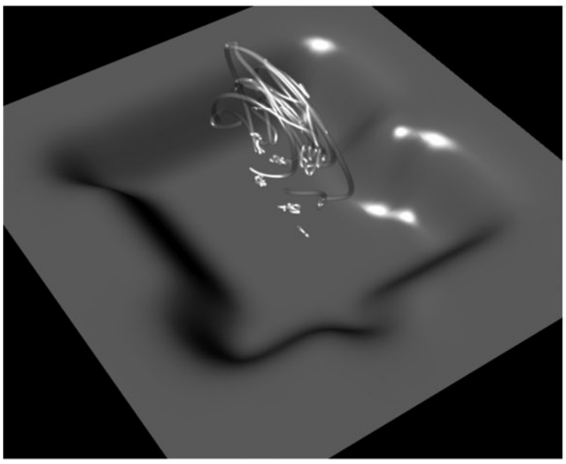
>> Surfaces by adjacent joints



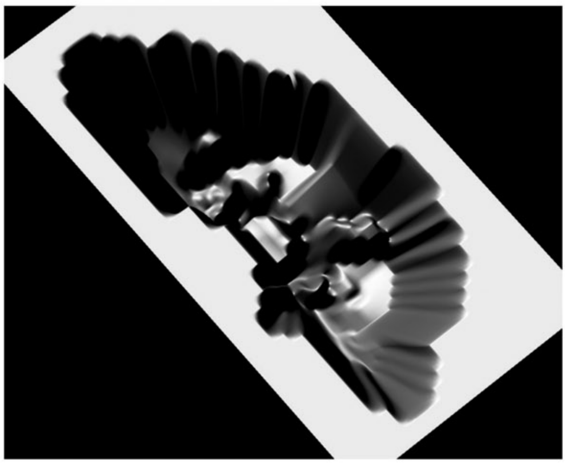
>> Grids

>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

>> Animation frames

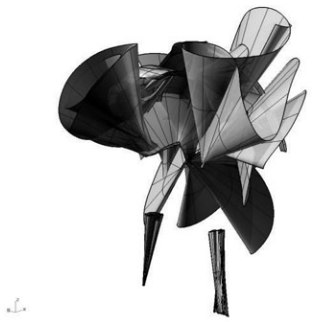
5.4_ bend over

// positive space //

>> Points

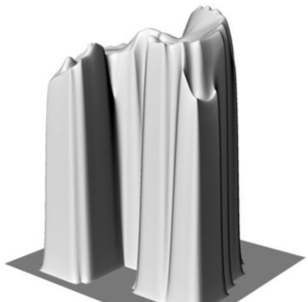
>> Lines

>> Surfaces by symmetrical limbs



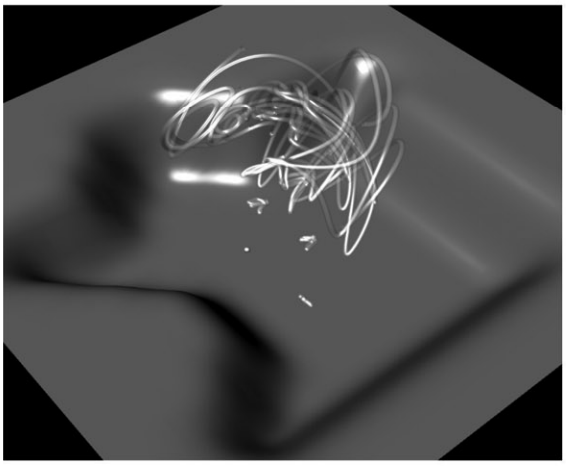
>> Surfaces by adjacent joints

>> Grids

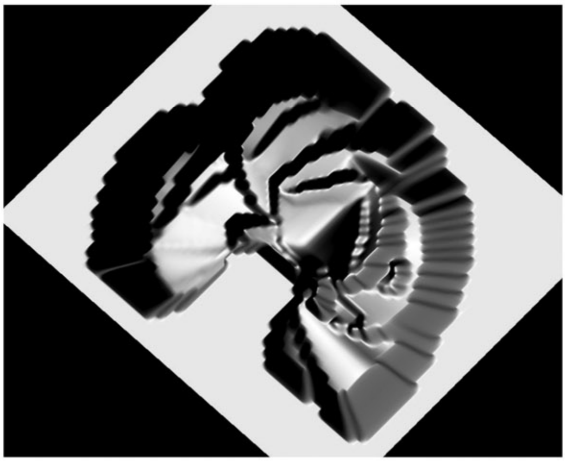


>> Volume by draping

// negative space //



>> Surfaces by repulse

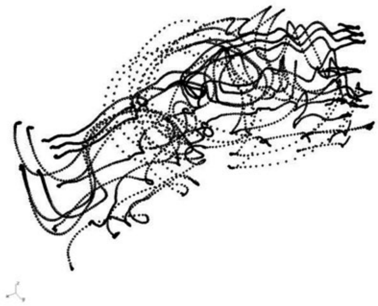


>> Volume by reverse draping

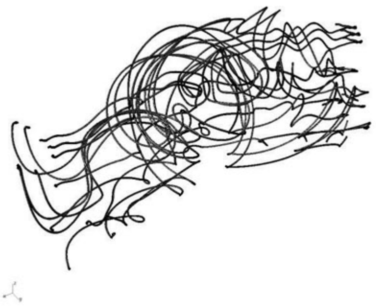
>> Animation frames

Seq.1_ small jetes, attitude/arabesque, shifted-axis pirouette, turn

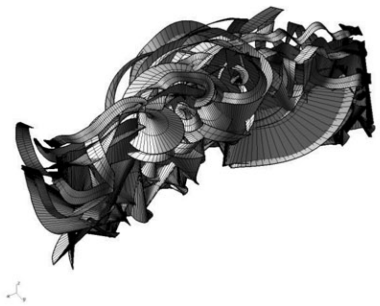
// positive space //



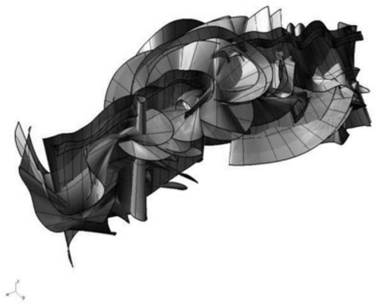
>> Points



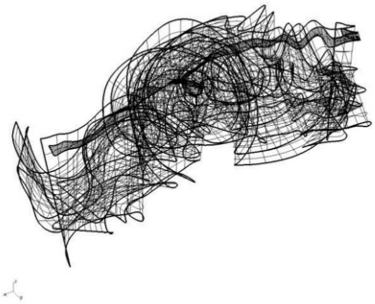
>> Lines



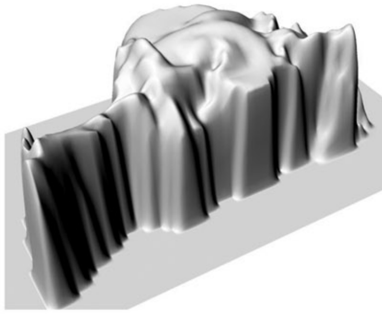
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

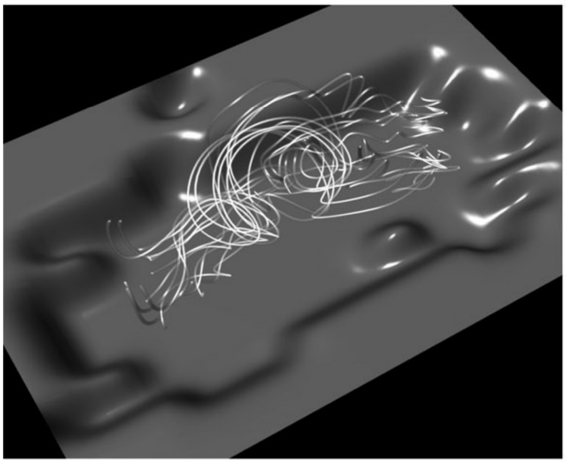


>> Grids

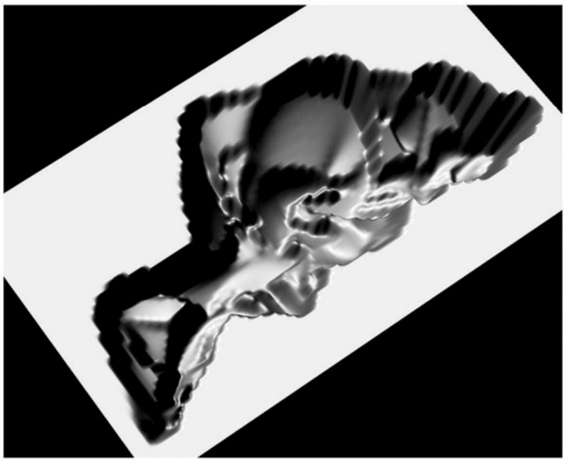


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

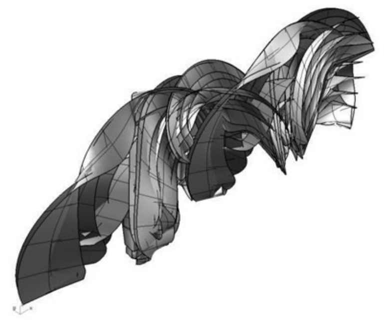
>> Animation frames

Seq.2_ cartwheels

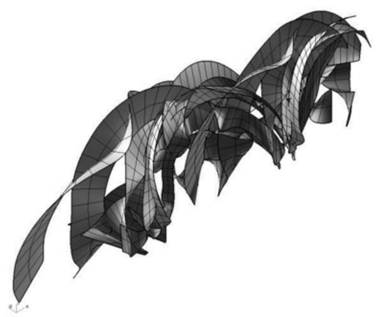
// positive space //

>> Points

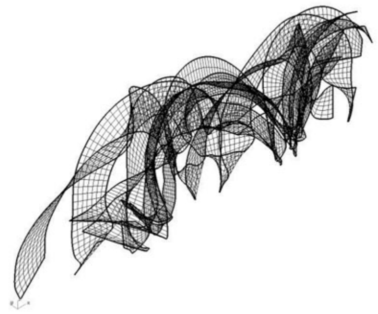
>> Lines



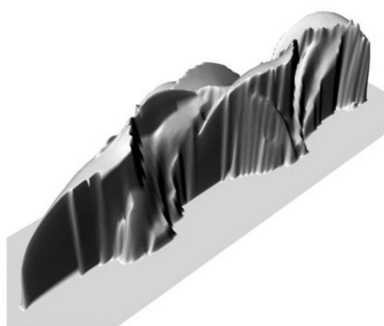
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

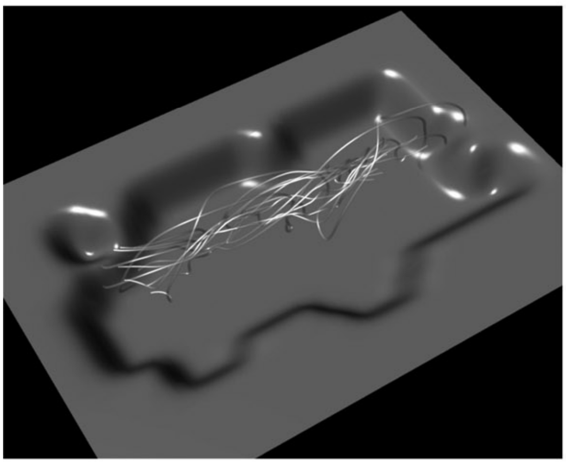


>> Grids

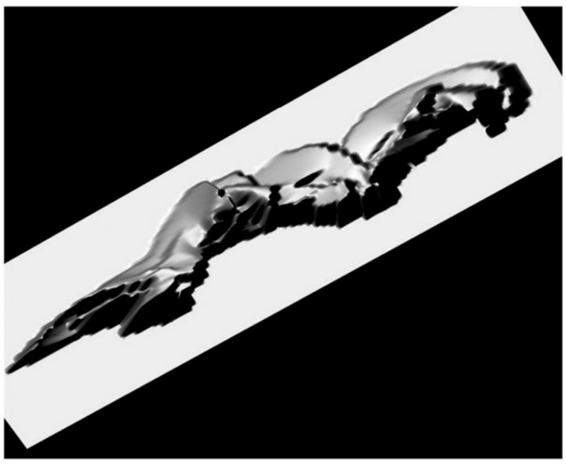


>> Volume by draping

// negative space //



>> Surfaces by repulse

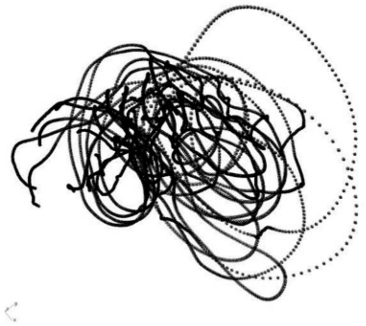


>> Volume by reverse draping

>> Animation frames

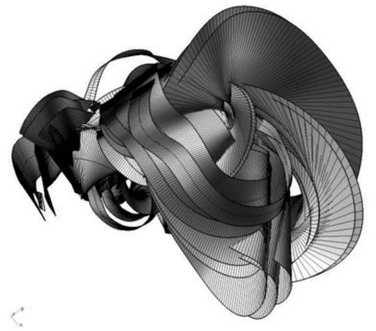
Seq.3_ twists lying on the back

// positive space //

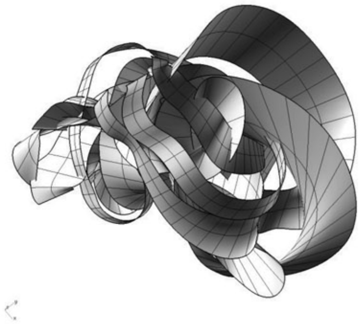


>> Points

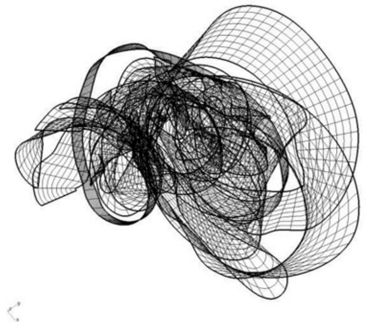
>> Lines



>> Surfaces by symmetrical limbs



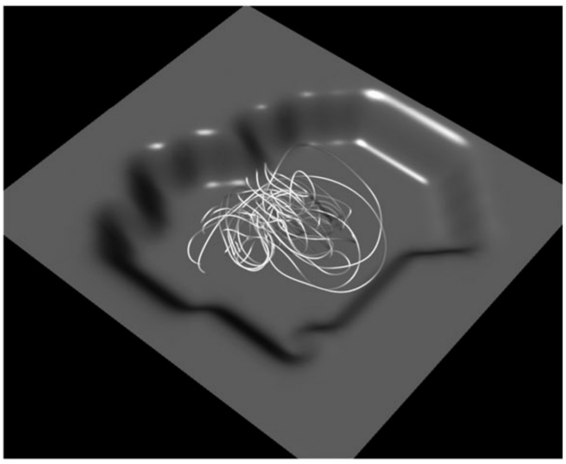
>> Surfaces by adjacent joints



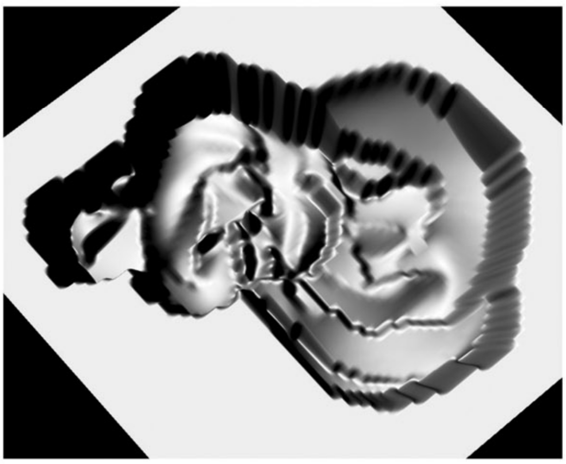
>> Grids

>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

>> Animation frames

5.5_ bend diagonally

// positive space //

>> Points

>> Lines

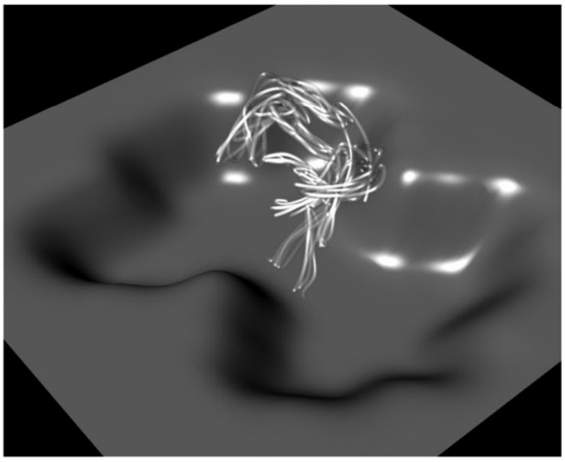
>> Surfaces by symmetrical limbs

>> Surfaces by adjacent joints

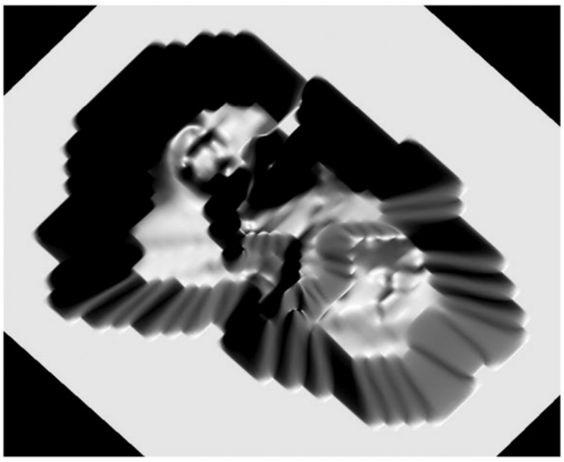
>> Grids

>> Volume by draping

// negative space //



>> Surfaces by repulse

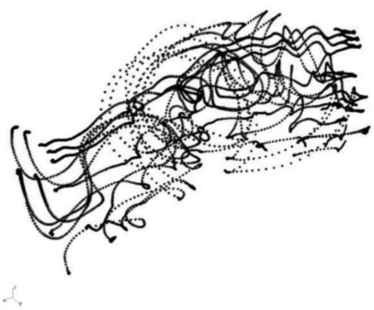


>> Volume by reverse draping

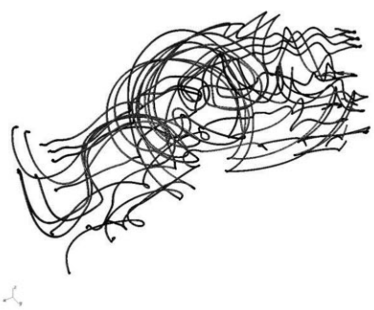
>> Animation frames

Seq.1_ small jetes, attitude/arabesque, shifted-axis pirouette, turn

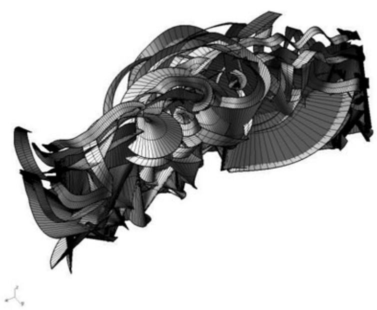
// positive space //



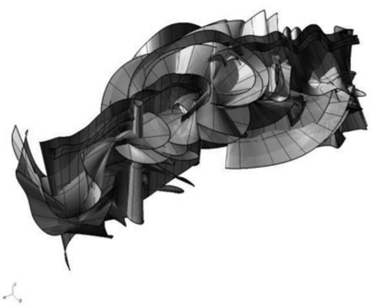
>> Points



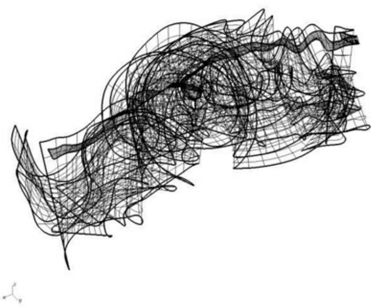
>> Lines



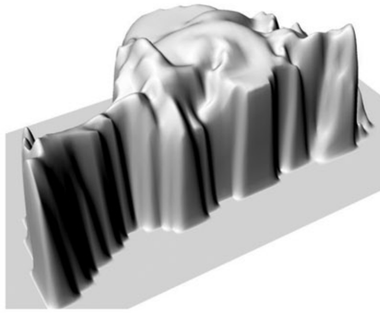
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

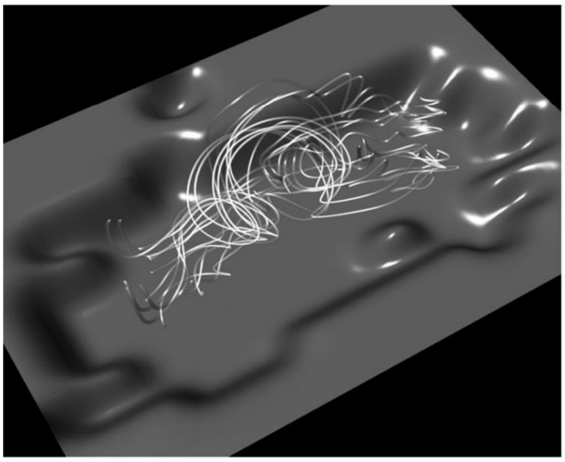


>> Grids

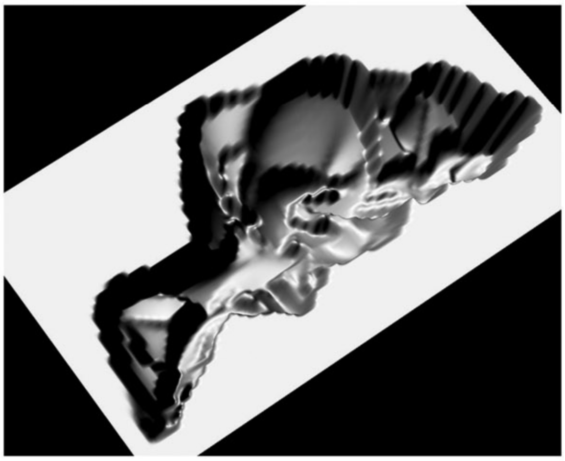


>> Volume by draping

// negative space //



>> Surfaces by repulse



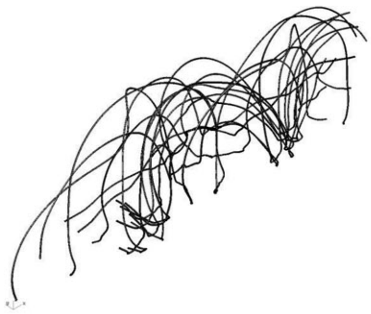
>> Volume by reverse draping

>> Animation frames

S e q . 2 _ c a r t w h e e l s

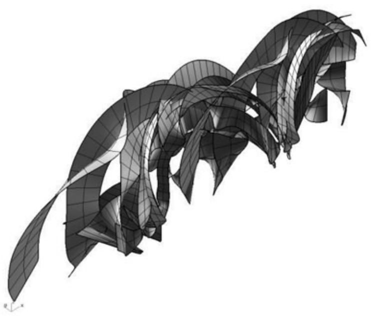
/ / p o s i t i v e s p a c e / /

>> Points

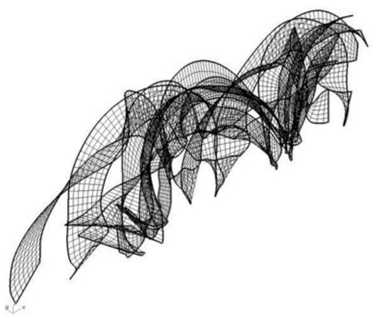


>> Lines

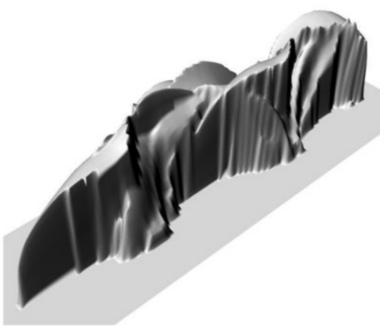
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

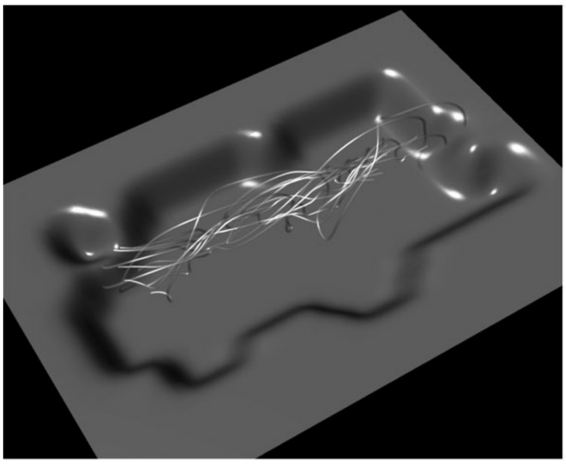


>> Grids

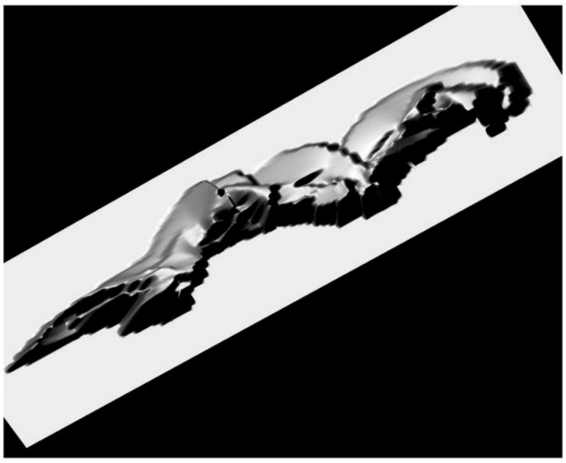


>> Volume by draping

/ / n e g a t i v e s p a c e / /



>> Surfaces by repulse

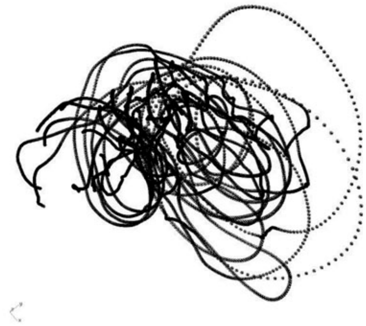


>> Volume by reverse draping

>> Animation frames

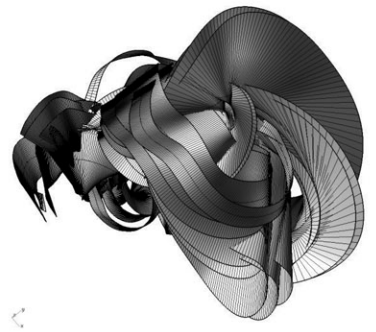
Seq.3_ twists lying on the back

// positive space //

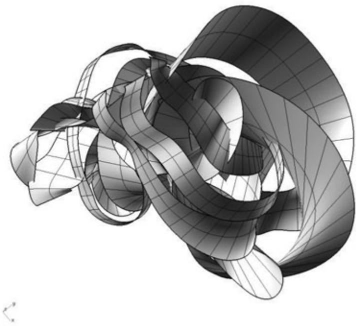


>> Points

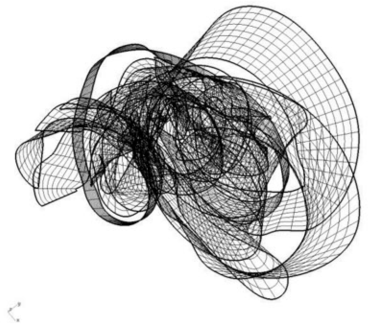
>> Lines



>> Surfaces by symmetrical limbs



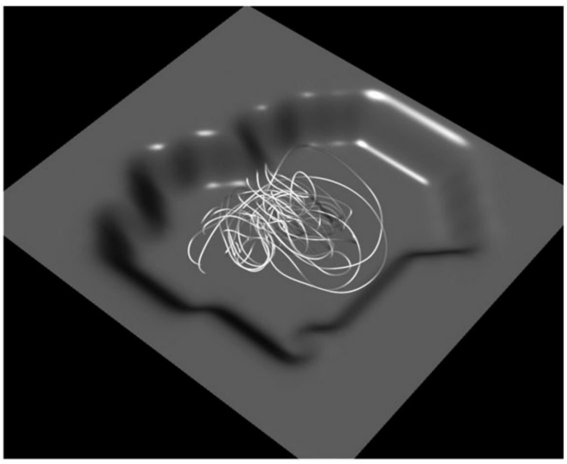
>> Surfaces by adjacent joints



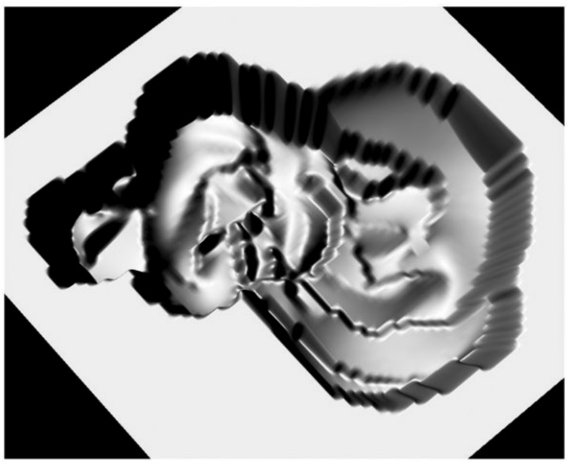
>> Grids

>> Volume by draping

// negative space //



>> Surfaces by repulse

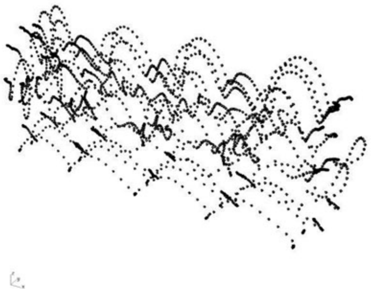


>> Volume by reverse draping

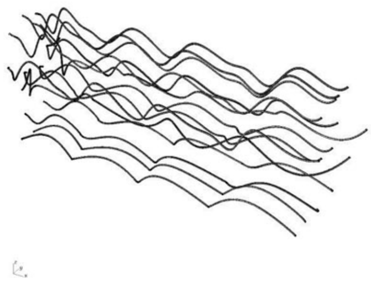
>> Animation frames

Seq.4_ forward jumps

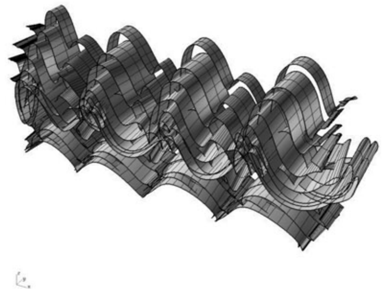
// positive space //



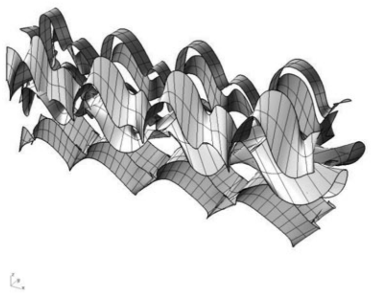
>> Points



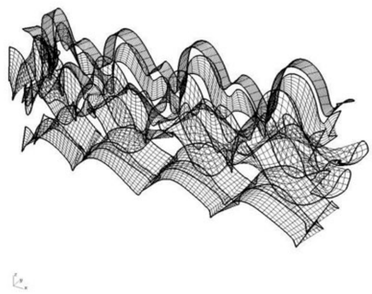
>> Lines



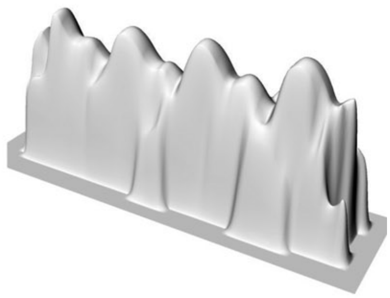
>> Surfaces by symmetrical limbs



>> Surfaces by adjacent joints

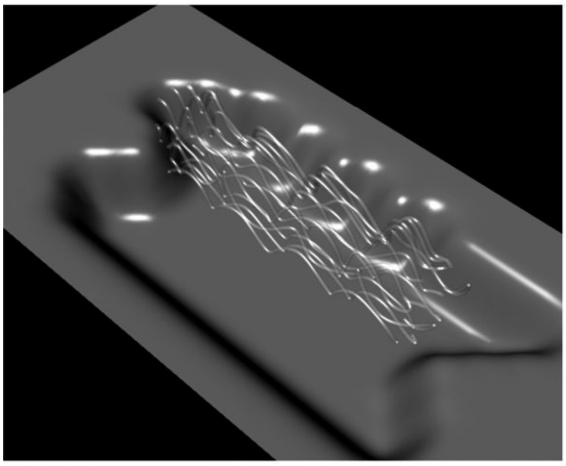


>> Grids

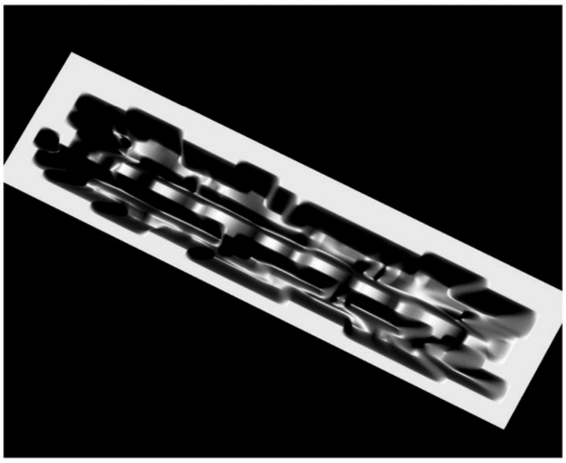


>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

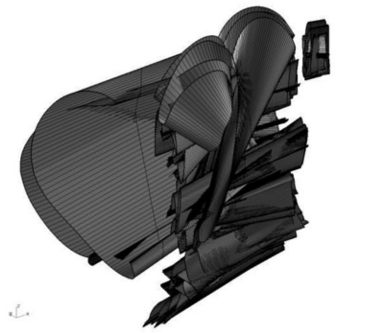
>> Animation frames

Seq.5_ alternating jumping jacks

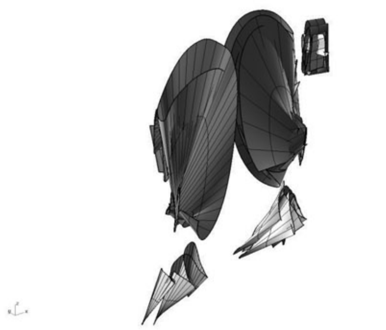
// positive space //

>> Points

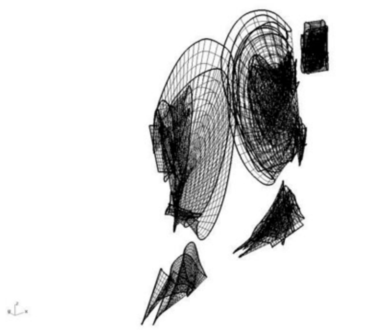
>> Lines



>> Surfaces by symmetrical limbs



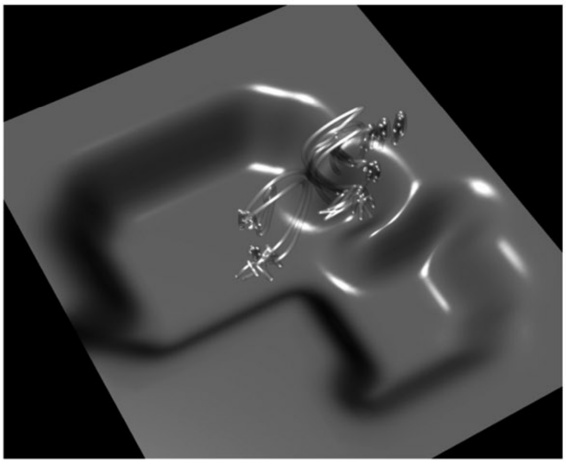
>> Surfaces by adjacent joints



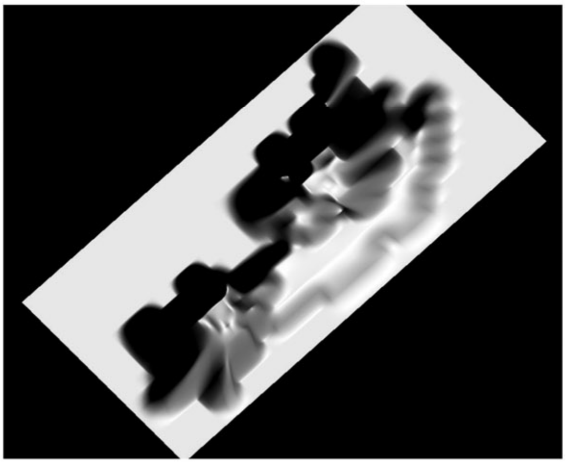
>> Grids

>> Volume by draping

// negative space //



>> Surfaces by repulse



>> Volume by reverse draping

>> Animation frames

APPENDIX_C | Parametric Definitions and Motion Data (CD)

CD

CD CONTENTS:

01. Motions' Library
02. Parametric Models' *Appendix*
03. *Rhino & Grasshopper Files*
04. Thesis