TRANSFORMING HUMAN BODY MOTION DATA INTO DEPLOYABLE 3D PERSONAL SPACES AND APPLICATION OF THIS DESIGN METHOD TO A CABLE-SUSPENDED PAVILION

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ABSTRACT

TRANSFORMING HUMAN BODY MOTION DATA INTO DEPLOYABLE 3D PERSONAL SPACES AND APPLICATION OF THIS DESIGN METHOD TO A CABLE-SUSPENDED PAVILION

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With the developing technologies, the design process can now be carried out in computational environments with an interdisciplinary approach. Thus, technological developments in various disciplines can easily affect and improve architectural design. Within the scope of this study, it was intended to bring together 3D motion capture (MoCap) technology, which is indispensable for the animation and gaming industry, and kinetic systems, which constitute one of the advanced technologies of architecture. These two disciplines are well suited to each other since the movement is the basis of both. The aim was to transform human body movements into 3D forms and to make these forms useful in an architectural sense, to function as a personal space. However, since the size of personal space can vary depending on many factors, the necessity of creating a dynamic form has also emerged. Within this scope, the literature review was carried out firstly on movement simulation, secondly on personal space, and finally on kinetic architecture. In light of the information gathered, an experimental study was carried out in two phases using 3Ds Max, Maya, Python, and Rhinoceros programs to transform human body motion data into deployable 3D personal spaces. In the first phase, varying forms of 103 human motions were created in the digital environment, and their diversity was evaluated. By using one of the created forms, a deployable cable-suspended pavilion was designed in the second phase of the study, which can be used for varying functional purposes such as relaxation, exhibition, or multimedia performance.

Keywords: Human-Body Motion Data, Motion Capture, Movement Simulation, Kinetic Architecture, Personal Space

ÖZ

İNSAN VÜCUDUNUN HAREKET VERİLERİNİN KATLANIP TAŞINABİLEN 3B KİŞİSEL ALANLARA DÖNÜŞTÜRÜLMESİ VE BU TASARIM YÖNTEMİNİN KABLO DESTEKLİ BİR PAVYONA UYGULANMASI

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Eylül 2023, 150 sayfa

Gelişen teknolojiler ile tasarım süreci artık disiplinler arası bir yaklaşımla hesaplamalı ortamlarda gerçekleştirilebilmektedir. Böylece çeşitli disiplinlerdeki teknolojik gelişmeler mimari tasarımı kolayca etkilemekte ve geliştirmektedir. Bu çalışma kapsamında animasyon ve oyun sektörünün vazgeçilmezi olan 3B hareket yakalama (MoCap) teknolojisi ile mimarinin ileri teknolojilerinden birini oluşturan kinetik sistemlerin bir araya getirilmesi amaçlanmıştır. Her iki disiplinin de temelinde hareket yatması sebebiyle bir araya gelişleri uyumlu bulunmuştur. Çalışmanın amacı, insan vücudu hareketlerini 3 boyutlu formlara dönüştürmek ve bu formları mimari anlamda kullanışlı hale getirerek kişisel bir alan işlevi kazandırmaktır. Ancak kişisel alanın büyüklüğü birçok faktöre bağlı olarak değişebildiği için dinamik bir form oluşturma gerekliliği de ortaya çıkmıştır. Bu kapsamda literatür taraması, öncelikle hareket simülasyonu, ikinci olarak kişisel alan ve son olarak da kinetik mimari üzerine gerçekleştirilmiştir. Elde edilen bilgiler ışığında, insan vücudunun hareket verilerini katlanıp taşınabilen 3B kişisel alanlara dönüştürmek için 3Ds Max, Maya, Python ve Rhinoceros programları kullanılarak iki aşamada deneysel bir çalışma gerçekleştirilmiştir. İlk aşamada 103 insan hareketinin dijital ortamda farklı formları oluşturulmuş ve çeşitlilikleri değerlendirilmiştir. Çalışmanın ikinci aşamasında ise oluşturulan formlardan biri kullanılarak dinlenme, sergileme, multimedya performansı gibi farklı fonksiyonel amaçlar için kullanılabilecek katlanıp taşınabilen kablo destekli bir pavyon tasarlanmıştır.

Anahtar Kelimeler: İnsan-Vücudunun Hareket Verileri, Hareket Yakalama,
Hareket Simülasyonu, Kinetik Mimari, Kişisel Alan

To my family, I couldn't have done this without your support.

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CHAPTER 1

INTRODUCTION

This chapter firstly provides background information on the relationships between human-body, its movement, and architecture, and on using movement data as a design ingredient. Then it continues with the sections problem statement, aim and objectives, research questions, research methodology, and disposition.

1.1 Background Information

The architecture of space is experienced and perceived through the movement of body(ies) in space-time. Hence, architecture cannot exist without movement, space, and time. Movement also affects space, just as space shapes movement. As Aguiar (2018) points out, they both interact and modify each other. Therefore, movement and architecture are concepts that cannot be considered separately.

Many studies have been made about movement, which is considered as one of the central issues in art and architecture from past to present. Especially in artistic fields, there are many creative applications that use 3-dimensional motion capture (3D MoCap) systems inspired by photographic motion studies. However, in this regard, Hirschberg et al. (2006) stated that in architecture, although contemporary architects have many designs on motion and dynamic form, they are far from using actual 3D movement data in their designs. However, architecture is inherently intertwined with movement so that movement can be considered at every stage of an architectural design, not just in the final outcome. The data that an architect can use when designing a space can be user requirements, inspiration, ideas, maybe a song, or the ever-changing body movements and perception of the user (Kırkan, 2015).

The view that a space for humans should be designed based on the data of human movements actually dates back to ancient times. According to Vitruvius, who lived in Ancient Rome, architecture was born from the instinctive actions of man while protecting his body against nature (Piedade Ferreira, 2003). In other words, the origin of architecture is based on body movements. Additionaly, Diniz (2008) and Piedade Ferreira et al. (2011) draw attention to body-tailored design which was born from Gaston Bachelard's idea of shaping a house 'in the same way a bird shapes its nest, with the movements of its body' and emphasizes the construction of space for the self. This means, for a user-centered design, it is natural and necessary to utilize user movement data as a design component. User-centered designs are flexible, responsive, and allow a sensorial and more subjective experience of space (Piedade Ferreira, 2003).

According to Hansen and Morrison (2014), body movement is the embodiment of non-verbal communication but before considering full-body movements as a design component, it is necessary first to explore how movements become meaningful. This form of communication can be read and perceived through computerized technologies so that important steps can be taken towards creating interactive designs.

However, when motion data is considered as a design material, the exploration of this material is not tangible like clay or concrete, so it is more appropriate to call it an 'ingredient' rather than 'material'. The designer can explore this ingredient by re-mapping the motion data, visualizing it, and inferring meaning from it.

Hence, it becomes essential to identify the particularities and properties of these movement data via digital tools which enable the designers to 'see' the data, extract information, evaluate which information is valuable, and eventually use it as a design ingredient in creating interactive spaces.

1.2 Problem Statement

With current technology, the design process can now be carried out in computational environments using an interdisciplinary approach. As a result, numerous disciplines' technical advancements can easily be used by architects. One of these advancements intended to be addressed in this study is 3D MoCap systems, which are indispensable in the animation and gaming industries. There are many studies and applications in the literature on the use of these systems in architecture. However, the generation and simulation of kinetic and interactive forms using actual movement data as the main design ingredient are still not fully explored. The examples put into practice are often on small scales, such as sculptures or art installations. Their use is still not common at architectural scales. A need for further research in this area is identified in order to fully realize the potential benefits offered by MoCap technology.

1.3 Aim and Objectives

This research aims to understand how human beings can give shape to their environment through movement and how an interaction between them and their surroundings can arise within that environment.

In order to achieve this aim, the objectives fulfilled in this research are to learn how movement data can be obtained and simulated, which directed the research to study motion capture (MoCap) technology, its origin, and technicalities. Then to learn and identify their future potential of use. Afterward, to present an overview of the development of kinetic systems, their benefits, and movement principles. Lastly, to examine personal space design requirements from proxemic and ergonomic perspectives. The intention is to generate a digital and a physical model of a kinetic personal space at the end.

1.4 Research Questions

The research questions that this study is expected to answer are:

- How can simulation of movement contribute to architecture?
- How can movement data be used to define space?
- Which movement types can be used for architectural purposes? Why?
- What are human movement patterns in personal space?
- How can a design adapt to the changing size and shape of personal space?

1.5 Research Methodology

The research began with revealing the existing methods and approaches on how movement data is handled in various disciplines through a literature review. The research was then carried out in two stages in line with the design method adopted, adapted, and improved from other fields. In the first stage, 3D forms were obtained by simulating human motion data in the digital environment. The second stage was continued through one of the obtained forms. To make this form kinetic, a supporting structure consisting of pantographic elements was designed. Thus, a system that can be contracted and expanded was obtained. As a result, a cable-suspended pavilion was created that could adapt to the changing and varied needs of personal space. The process of this study is briefly shown in Figure 1.1.

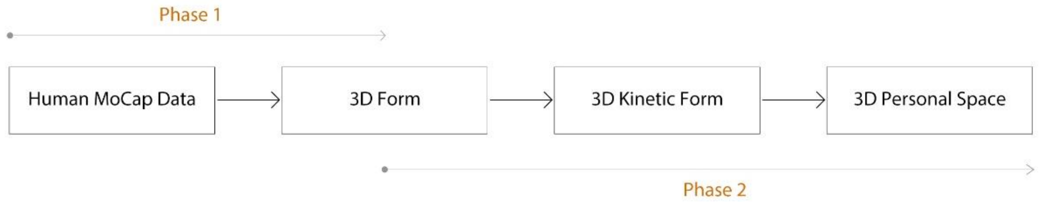


Figure 1.1. Transforming Human-Motion Into 3D Personal Space

1.6 Disposition

In this research, the first chapter introduces background information on the relationships between body, movement, and architecture and on using movement data as a design ingredient. Then indicates the problems, aim, objectives, research questions, and methodology. The second chapter is dedicated to the literature review, which presents, firstly, movement simulation, secondly, personal space in architecture, and lastly, kinetic systems in detail. The third chapter is about the materials and methods used in this study, and the outcomes obtained are presented in the results and discussion chapter. The last chapter is the conclusion giving brief information about the research and its findings.

CHAPTER 2

LITERATURE REVIEW

The literature review presented in this chapter addresses the issues of considering human-body movement in spatial design by utilizing motion capture data; the concept of personal space with respect to ergonomics and proxemics in design and the integrating of the above mentioned concepts into kinetic architecture that is deployable.

2.1 Human-Body Movement

Taking movement, use of space and body as a basis in architecture dates back to ancient times; according to Davis and Altevogt (1979), Roman architect Marcus Vitruvius Pollio in his treatise named De Arquitectura (c. 25 BC) had emphasized a similarity between the perfect building and the human body by placing the body in the circle and square, and stated that "Nature has designed the human body so that its members are duly proportioned to the frame as a whole." Hence, according to Vitruvius, the human body is perfectly proportioned and contains harmony in all its parts; therefore, the human body should be taken as a basis in order to build a perfect building. While Vitruvius was working on finding the perfect ratio in architecture and the human body, he also introduced the concept of ‘module’ to architecture (Kırkan, 2015). As an example, modular proportions were used in constructing the Parthenon in Athens. The theories he included in his treatise inspired the Middle Ages and the Renaissance.

Inspired by the work of Vitruvius, Leonardo da Vinci created the most famous descriptive drawing of the human body, described in a circle and square. Man is not static in this drawing but standing and in motion (Piedade Ferreira et al., 2011). With this early period example, the idea of working with proportions artistically and scientifically gained importance (Kırkan, 2015).

The other person who added a further dimension to the subject was Le Corbusier. He continued the idea of discovering mathematical proportions in the human body and applying them to architecture. Davis and Altevogt (1979) stated that the proportions of the good-looking human body with the arm up in Le Corbusier's sketch called The Modular, drawn in 1946, are based on the Fibonacci system and the Golden Ratio. This visual scale system acts as a bridge between metric and imperial systems. However, according to Piedade Ferreira et al. (2011), The Modular started to lose its value over time because this system of rules based on universal human description is static, inflexible, abstract, and close to differences. However, it should not be ignored that the approach of Le Corbusier showed the way towards an architecture that combines reason and intuition.

Le Corbusier pursued a scientific, aesthetic concern. In his works, he aimed to provide a balance between man and his environment. His movement studies on the use of space in architecture became the means of designing new forms and spatial transitions. In the research of Louw (2016), his architecture was defined as an embodied experience of movement through space instead of architecture as a static experience. Le Corbusier preferred the word 'promenade' instead of the word circulation and suggested the concept of 'promenade architecture.' In this concept, architectural spaces gradually emerge by using the body's movement as an experiential device. For example, in Le Corbusier's Villa Savoye, the interior and exterior are intertwined. After breaking away from the fast rhythm of the city and reaching Villa Savoye, the roof can be accessed via the outer ramp with a slow walking pace, and a new relationship with nature can be established through the window at the end of the ramp (Louw, 2016). This design supports the idea that body movement is an essential input that an architect must address for the perception and definition of space.

An architectural space, the design of which will be created by considering the movement input, does not force or limit the user's body movements; instead, it enables, adapts to, and responds to them. Therefore, the designs to be formed are more flexible and dynamic rather than rigid forms. To obtain such designs, there should be no limitations in the relationship between human body movements and architecture, as in the Modular system. For this, it is necessary to translate the movement into the language of mathematics and to discover the spatial relations of the dynamics of the human body there. According to Piedade Ferreira et al. (2011), transferring movement to the programming language with the help of digital technologies in the field of industrial design has allowed body-tailored designs that are flexible, responsive, and smart. Thanks to similar systems frequently used in the animation industry, all kinds of objects and geometries can be designed parametrically (Piedade Ferreira et al., 2011). In these designs, even Euclidian limitations can be overcome, and simulations can be made for varying conditions.

There are many researchers in different fields studying movement for various purposes. Analysis and documentation of movement for the sake of these purposes require demonstrations and simulations of it. However, this is not an easy task as movement happens in time and space and disappears the moment it is finished. Jensenius (2007) argues that although recording movements as a video can present them in time efficiently, this way is not efficient in analyzing and representing movements. In addition, taking a picture also does not represent the continuity of movement as it only captures one pose. For this reason, it is necessary to make use of simulation techniques to demonstrate the way movement is perceived.

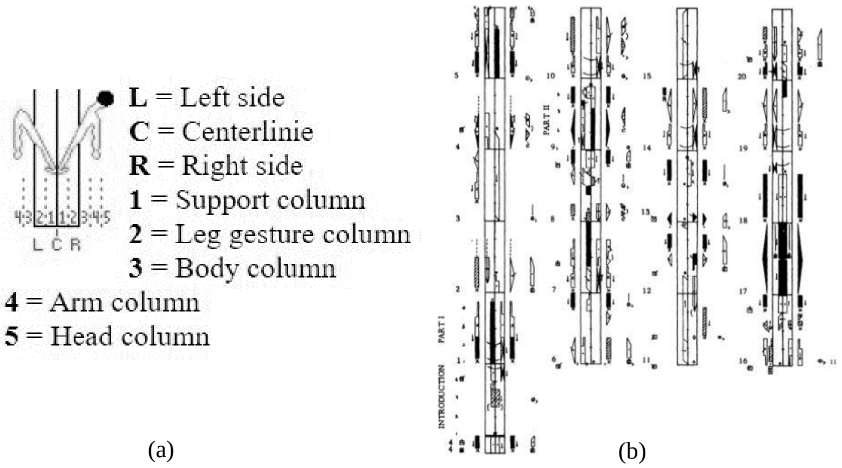
The human brain can perceive a continuous movement as a whole, divide it into parts to understand the effort, goal, and path of the action, and at the same time, can ‘see’ the entire unit of action before it ends (Jensenius, 2007). Today, this mental imagery process is tried to be attained in the computer environment to develop visual representation techniques that will allow the analysis of movements.

Accordingly, information on various techniques developed throughout history to capture, visually represent, and simulate movement was explained further in this chapter. It starts with the notation and abstraction of movement. Then follows an overview of motion capture (MoCap). Finally, it gives examples of MoCap applications in architecture.

2.1.1 Movement Notation and Abstraction

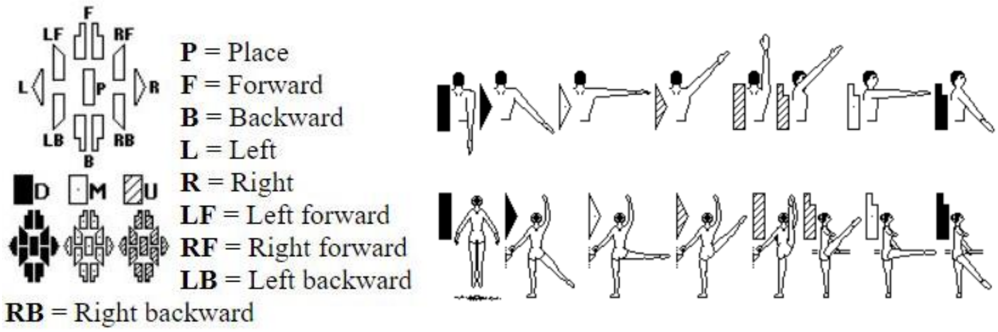
Notation is a tool to communicate ideas. As Harris (2002) stated, it is an interface that transforms ideas in all forms, whether architectural, musical, linguistic, or visual, into objects. For instance, according to Misi (2007), 'Writing represents speech with a sequence of letters.' Likewise, notes in music are also a notation system.

When considering it for movement, Hansen and Morrison (2014) mentioned that the first movement-specific notation system has emerged from dance, and Stathopoulou (2011) indicated that the most commonly used system in dance is Labanotation. This notation system was developed in 1928 by Rudolf Von Laban, one of the pioneers of contemporary dance. He focused on how to record dancers' movements through notation and called his approach 'choreology'. His purpose was to preserve the dance choreographies for future reference (Hutchinson, 1970 as cited in Stathopoulou, 2011). Accordingly, he invented a standardized notation system called Labanotation, or in other words Kinetography Laban (Kırkan, 2015). This system helps to analyze and record every kind of human body movement in terms of dynamics, time, and spatiality. For instance, there are symbols describing body parts, dancer's positions, movement's directions, paths, turns, levels, duration in time, and many more (Stathopoulou, 2011). Another notable aspect is that it is not connected to a specific type of dance, making it an extensive and flexible system (Griesbeck, n.d.). In this way, every change in the human body can be written down in detail via this notation (Figures 2.1, 2.2, and 2.3).



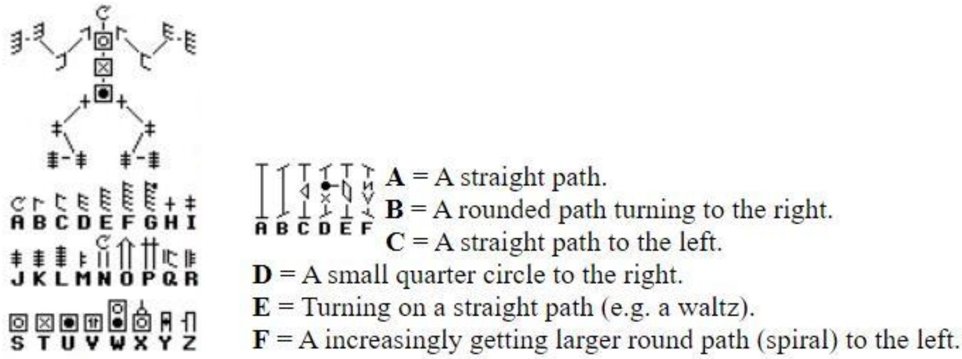
(a) (b)

Figure 2.1. (a) The Stave Consisting of Columns in Labanotation (Griesbeck, n.d.), (b) Laban Notation of Bournonville Classical Ballet, Adagio, 1979 (Guest, 1990 as Cited in Kırkan, 2015)



(a) (b)

Figure 2.2. (a) Some Basic Symbols of Labanotation: Horizontal Directions, (b) Arm and Leg Gestures and Their Directions (Griesbeck, n.d.)



(a) (b)

Figure 2.3. (a) Some Basic Symbols of Labanotation: Body Parts, (b) Paths (Griesbeck, n.d.)

In order to analyze movement, Rudolf Von Laban categorized it into ‘body, effort, shape and space’ in his studies (Figure 2.4). Based on this, Labanotation was then developed into Laban Movement Analysis (LMA) to describe both conscious and unconscious human movements and analyze their qualities (Bernstein et al., 2015). Although its foundation is based on dance, nowadays, it is being used in various fields such as physical therapy, behavioral science, athletics, acting, and even in art and architecture. In LMA categorization, ‘body’ deals with body parts and their relations with each other, while ‘effort’ comprises of space, weight, time, and flow. Laban believed that the variations of effort continue throughout the performance to transmit the influential information conveyed by ‘shapes’, which act as a bridge between body and space (Kırkan, 2015). On the other hand, ‘space’ comprises of the space occupied by the body and the space around it, which are investigated under the subcategories of kinesphere, spatial intention, and geometry.

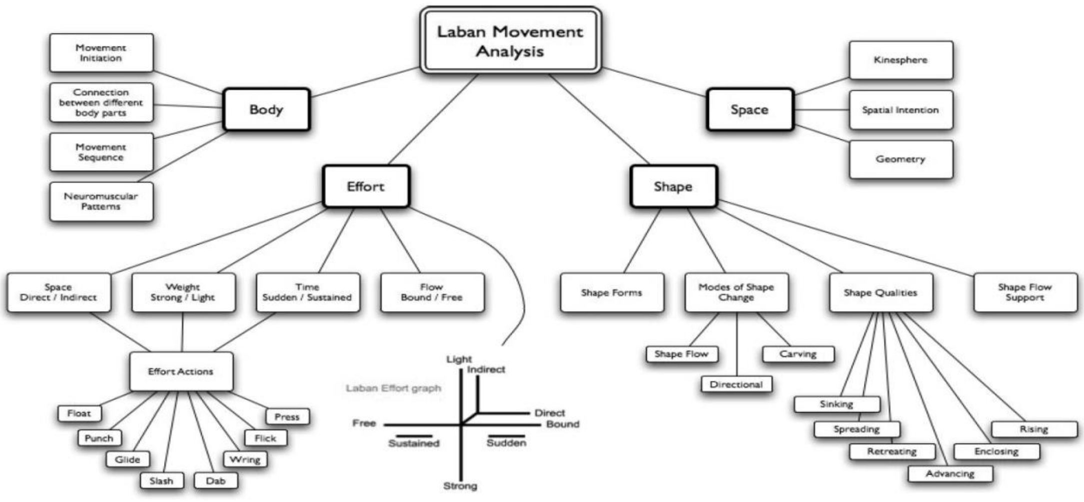
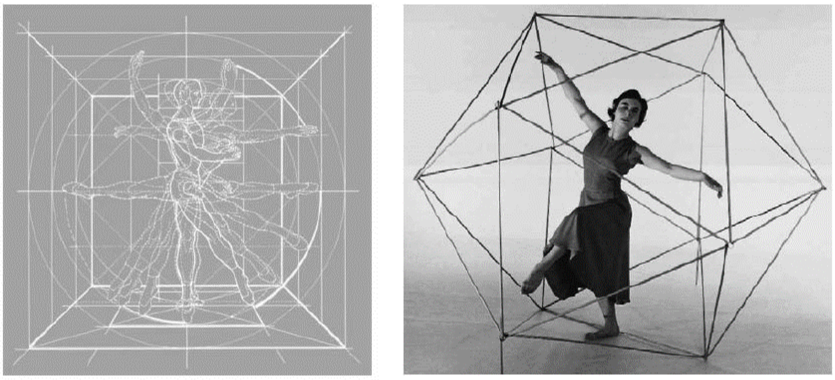


Figure 2.4. Laban Movement Analysis Table (Groff, 1995, as cited in Bernstein et al., 2015)

Kinesphere, which evolves under ‘space’ in the LMA table, is a spatial geometry used by Laban to generate the structure of the movement. In the research of Spurr (2007), it is defined as a three-dimensional geometry generated from 27 points in space, each of which can become the center of gravity (Figure 2.5.a). In this respect, it is very different from Vitruvius’s depiction of a person enclosed in a circle and square having one center of gravity. Considering the real limits of the human body, Laban defined kinesphere as a virtual icosahedron (Figure 2.5.b) that encompasses the entire space that an outstretched body can potentially reach (Stathopoulou, 2011). It covers all the positions of the body, and as the body moves, the icosahedron moves with it.



(a) (b)

Figure 2.5. (a) Kinesphere with 27 Points Marked, (b) The Icosahedron: Laban's Structure of Movement (Stathopoulou, 2011)

Even though a movement-specific notation system was first created for dance, there are other notation systems developed outside of dance as well. For example, Hansen and Morrison (2014) highlighted two key notation systems: 'proxemics' and 'kinetics'. Proxemics belongs to the anthropologist Edward T. Hall, and it studies the way people organize the spaces and distances they put between each other, which differs between cultures. In this notation, the body is only considered as a location in space (More detailed information is given in section 2.2.1). In contrast, kinetics devised by anthropologist Ray Birdwhistell analyzes the everyday movements of people from the perspective of functionality and anatomy. Hansen and Morrison (2014) believe that although these two notation systems deal with movement, they do not focus on the semantic properties of the dynamics of movement. The term dynamics of movement was first used by Laban and described as the result of energy used in time (Stathopoulou, 2011).

What can be deduced from all this is that in the notation and abstraction of movement for communication, structural details of the body should not be given too much attention as they miss the vitality of the movement. Therefore, while notating and abstracting movement for interactive design, it is necessary for designers to represent the moving person's perspective in their approaches in order to preserve and reflect the felt, lived experience (Loke & Robertson, 2013). In this framework, Hansen and

Morrison (2014) developed a digital tool called Sync, which can read and visualize full-body movement data (Figure 2.6). This tool can create different visuals on the same movement type by focusing on different aspects of that particular movement and presenting it with varying simulation choices (Figure 2.7). Hence, the outputs highlight various attributes of the movement data (Hansen & Morrison, 2014).

This kind of notation technologies using digital tools enables the designers to ‘see’ the data, extract information, evaluate which information is valuable, and finally to use it as a design ingredient in creating interactive spaces.

Figure 2.6. The Depth Data Obtained Through Kinect Sensor and the Set-up Running the Sync Tool (Hansen & Morrison, 2014)

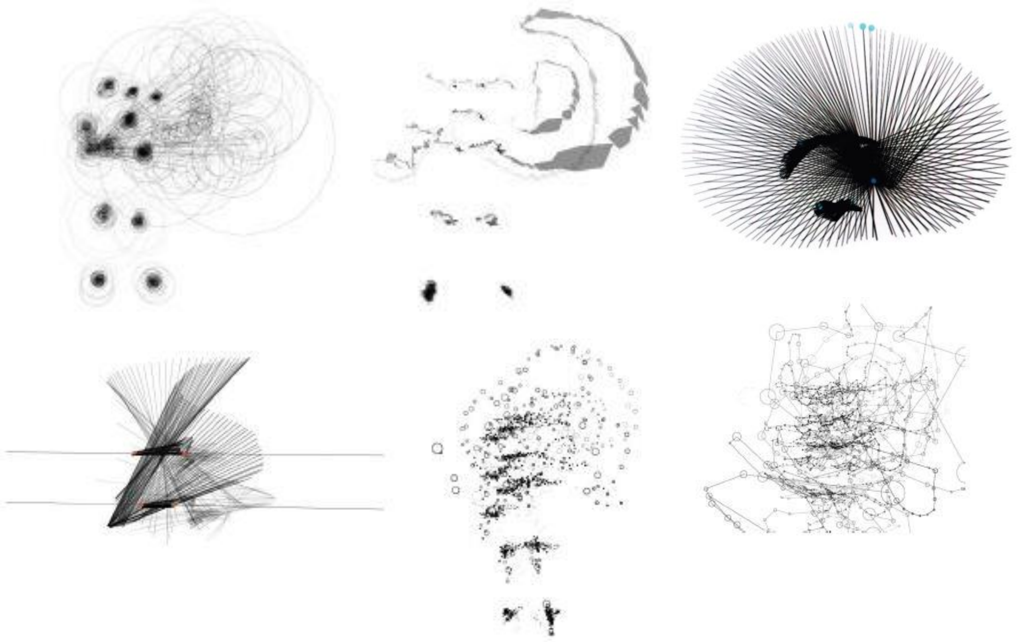


Figure 2.7. The Visuals Obtained Through the Sync Tool by Interpreting the Data of Full-Body Movement. Each Way of Representation Shows Different Aspects of the Data (Hansen & Morrison, 2014)

2.1.2 Motion Capture (MoCap)

According to Ebenreuter (2005), the notation systems allow to record and represent movement to communicate ideas, and motion capture is one of the commonly used notation technologies. It allows for a precise recording of movement. Its origin and ways of capturing motion is explored further below.

2.1.2.1 Origin of MoCap

According to Jensenius (2007), the visualization of movement has begun for anatomical studies on the movement of humans and animals. This made a tremendous impact in the field of photography at the end of the 19th century. Eadweard James Muybridge, who is one of the pioneers of this field, demonstrated the movement of a horse (Figure 2.8) in the 1870s in a series of pictures called "time-lapse photographs" by using high-speed cameras (Jensenius, 2007). In his visualizations, the movement could only be read temporarily, and the relationship with space could not be perceived.

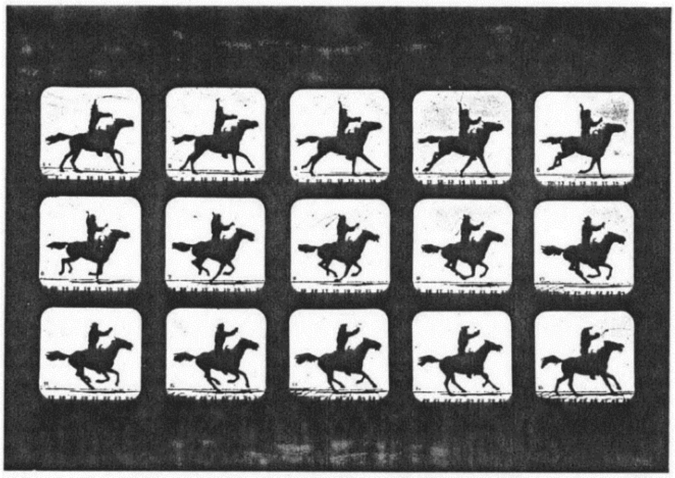


Figure 2.8. 'Vaquero and Rialto' from Eadweard Muybridge's Motion Study of "Attitudes of Animals in Motion" (Sheldon, 1989)

Another expert who worked on the visualization of motion in the field of photography is Étienne-Jules Marey (Jensenius, 2007). He lived at the same time as Muybridge. Unlike Muybridge, he showed movement in a single photograph, which he called 'pictures of time', rather than a series of pictures. In this way, both the continuity of the movement and its relation with the space can be read in the same frame. In his work (Figure 2.9), while the horse moves slowly, its body in each pose is clear, but while the horse moves fast, the body in the poses loses its clarity. Although this allows to detect the speed changes of the movement, the overlapping poses cause confusion in perceiving the motion's content.

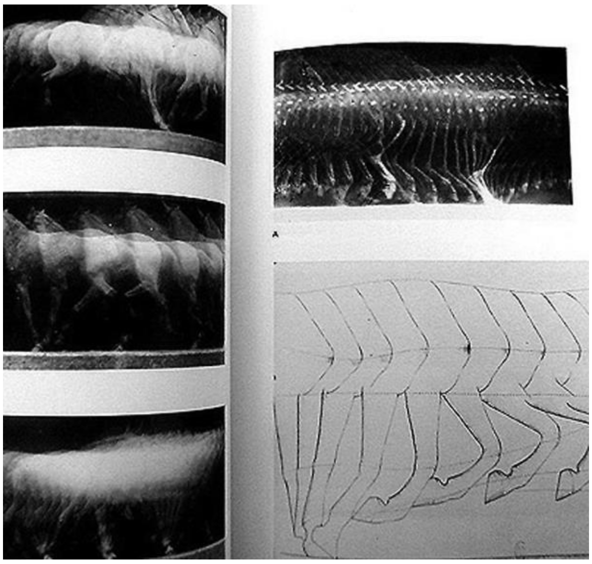


Figure 2.9. The Study of the Movement of a Horse by Étienne-Jules Marey (Sevaldson, 2005)

In order to solve this, Marey captured the movement of a human wearing a black outfit with metal sticks on his limbs (Figure 2.10) (Stathopoulou, 2011). In this way, he was able to capture the essence of the motion independently of the physical characteristics of the subject. With this technique, Marey laid the foundations of motion capture by only visualizing the markers on a single photograph.

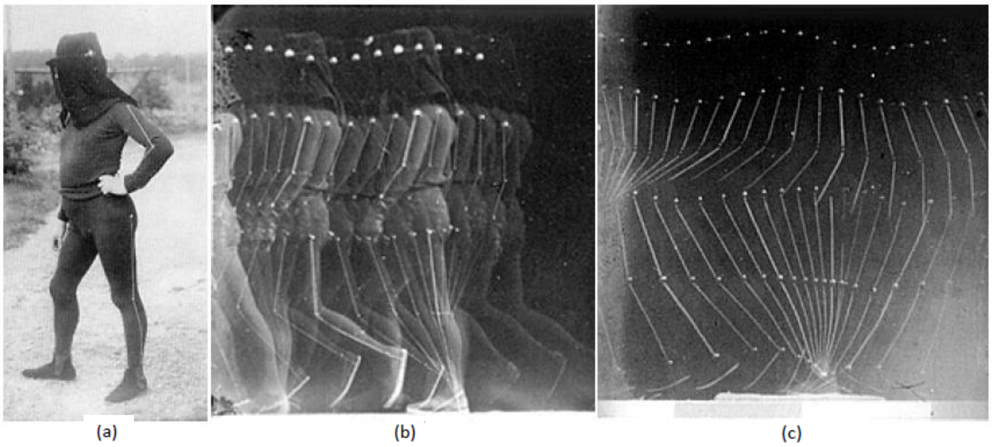


Figure 2.10. (a) Motion Capture Suit of Marey, (b) Overexposed Photograph Showing Both the Body and the Markers, (c) Photograph Showing Only the Markers (Stathopoulou, 2011)

A similar technique was developed by Gunnar Johansson nearly 100 years later (Jensenius, 2007). In his study, which is called the Johansson experiment, he placed reflective markers on the joints of the human body (Figure 2.11) and captured them with the help of a video recording technique. In this way, he visualized only the movement of the joint points in space. With this study, it was understood that movement types such as walking, running, and jumping could be perceived even from only a limited number of points set. This gave the idea that points put on the critical parts of the subject/object can be used to capture human motion, or any other rigid or non-rigid motion. The current advanced versions of this technique are optical marker-based motion capture systems. The subject is surrounded by many infrared cameras, and the 3D coordinates of the sensors located on the subject are captured and transferred to digital platforms to be used mostly in the creation of animations in the film industry (Jensenius, 2007). Moreover, these systems are also used in medical applications and the set-ups of Virtual Reality (VR) and Augmented Reality (AR) (Hirschberg et al., 2006).

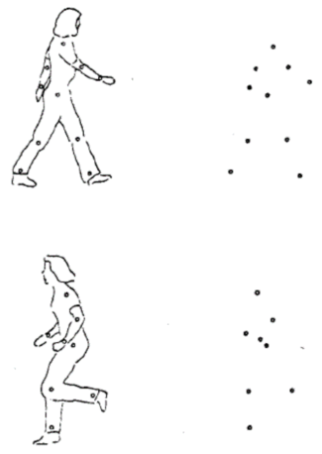


Figure 2.11. Representation of a Walking and a Running Subject in Dots (Johansson, 1973)

There are many emerging uses of motion capture systems in various fields as well. In particular, besides visualizing the captured data as a digital human model, there is a lot of research reported in the literature on turning digital point data retrieved from any motion into a form. One of them is MoSculp which is a research project at the MIT Computer Science & Artificial Intelligence Lab (Zhang et al., 2018). This research aims to represent the continuous movement path of athletes with a form (Figure 2.12). Thus, other athletes can improve themselves by analyzing the traces of a movement that has brought success in the related sports branches.

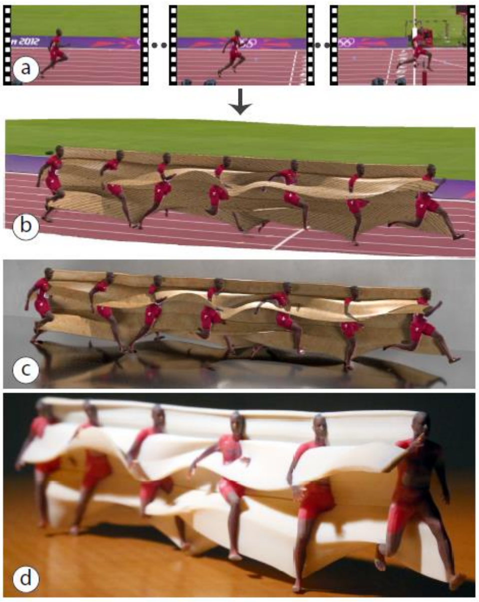


Figure 2.12. MoSculp's Creation Process. (a) The Input Video, (b) Virtually Created Sculpture Within the Original Video, (c) Rendered Sculpture in a Synthetic Scene, (d) 3D Printed Sculpture (Zhang et al., 2018)

2.1.2.2 Ways to Capture Human Motion

Besides the optical motion capture system mentioned in the previous section, three more systems have been developed from past to present to capture motion. Overall, MoCap systems are mechanical, electro-magnetic, optical, and video-based. These methods provide the documentation of movement via sensors or markers usually attached to the mover’s body. The captured data's efficiency and degrees of accuracy can vary depending on which method is preferred (Ebenreuter, 2005).

Among these methods, the mechanical MoCap system uses mechanical sensors which can collect very high-resolution of information, so it is mostly error-free. However, the mover is required to wear clothing having metallic pieces on it or needs to carry a portable datalogger which may restrict the flow of movement. On the other hand, the electro-magnetic MoCap system requires wearing a commercial smart suit with electro-magnetic sensors on it. To avoid interference from other magnetic fields, it is necessary to capture motion in a space free from metallic objects (Ebenreuter, 2005). These suits are mainly used for industrial purposes. Among MoCap systems, the most widely used one is the optical MoCap system. The movement is captured from a distance by optical means such as cameras and visual sensors. This method challenges many problems, such as occlusions, glare, reflections, or recognizing markers. Hence it has a lengthy editing process, and the types of environments that these systems can be used in are limited (Hirschberg et al., 2006). However, it provides very precise motion data at the end to be used for the generation of naturally looking animations (Hirschberg et al., 2006; Stathopoulou, 2011). Finally, the video-based MoCap system captures motion from a single camera rather than multiple cameras. This becomes possible by deep learning, which uses a vast amount of data.

2.1.2.3 MoCap in Architecture

There are many emerging uses of MoCap systems in various fields. In the field of architecture, Hirschberg (2006) highlighted three potential areas where MoCap systems can be used to explore ‘the hidden beauty’ of human movement. These areas are ‘interacting with spaces’, ‘spatial analysis’, and ‘form generation through movement’, described below.

i. Interacting with space

Hirschberg (2006) states that using mo-cap and tracking systems allows a new way of interacting with spaces. For instance, when the users' movements are simultaneously tracked and linked to the functions of a room, the room can react to the users; hence communication arises between the building and its inhabitants. In this way, as Mahdavi (2005) stated, the building becomes sentient. This new way of interacting with spaces through body movement provides a more natural way of communicating with the buildings' technical systems than using remote controls. In addition, multiple users can communicate with the building at the same time, as opposed to using remote control by a single user (Hirschberg, 2006).

ii. Spatial analysis

Spatial analysis using motion capture and tracking systems is a new type of post-occupancy study. By analyzing how spaces are being used by people, architects can assess the architectural qualities of these spaces. For instance, by setting up optical tracking systems in a building, the movement traces of occupants can be obtained, and then the spatial performance of that building can be evaluated (Hirschberg, 2006). Accordingly, the design can be improved for future projects.

iii. Generating form through movement

Analyzing movement as 3D forms by means of MoCap systems can reveal new design potentials. Among these systems given information on in section 2.1.2.2, the optical MoCap system is the most preferred one for converting movement data into a form in the researches relevant to architecture. Hirschberg's research conducted in 2006 is one of them. Different motion scenarios were captured through a workshop and translated into wooden motion sculptures (Figure 2.13), whose forms are difficult to think of in a usual architectural design process.

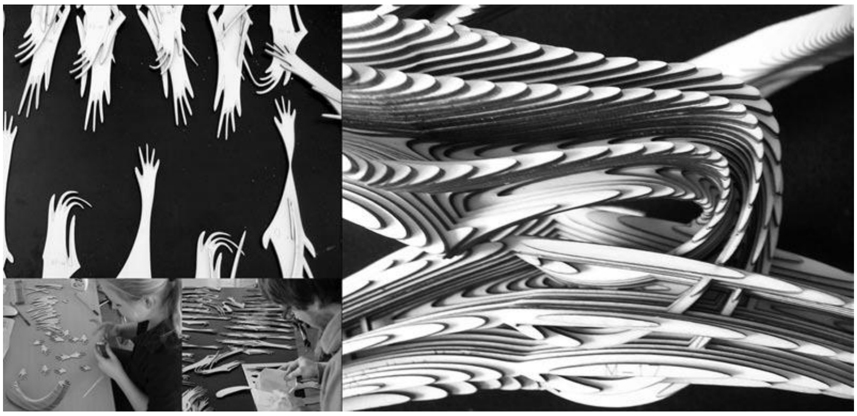


Figure 2.13. One of the Workshop Outputs, Wooden Sculpture of 'Clap Your Hands' (Hirschberg et al., 2006)

Another research examining how to generate new forms out of optically captured movement data belongs to Matsushima et al. (2007). This study aimed to develop a methodology for the transition from motion to form to extend the use of actual motion in architectural design. The authors preferred the action of walking in their study (Figure 2.14). After capturing and tracking the movement, an animation was created from the obtained data, and its trajectories were converted into a surface geometry to create a virtual prototype (VP) model in the software 3ds Max. Then a rapid physical prototype (RPP) model was generated with a 3D printer to analyze its visual and aesthetic quality (Figure 2.15). The study proved that complex shapes could even be created from simple movements.

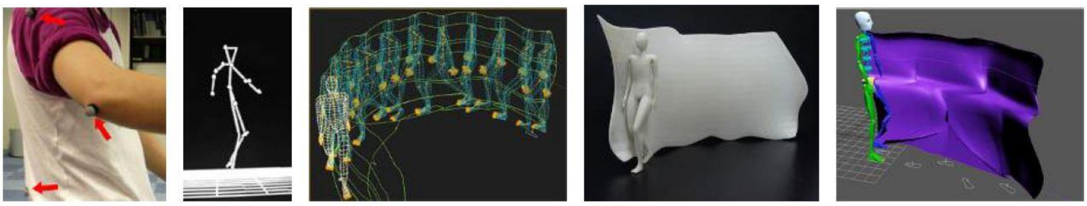


Figure 2.14. Process of Generating Form out of Captured Walking Movement (Matsushima et al., 2007)

(a) (b) (c)

Figure 2.15. (a) Placement of the Optical Markers, (b) The Generated Virtual Prototype (VP) Model, (c) The Rapid Physical Prototype (RPP) Model (Matsushima et al., 2007)

Stathopoulou (2011), on the other hand, did not capture human movement in his research. Instead, she retrieved movement data from the database of Carnegie Mellon University. The movement types that this database includes were captured via the optical MoCap system, and the 3D data is presented in more than one format. The ".c3d" format, which contains the frame rate and changing x, y, and z coordinates of the markers throughout the movement, was preferred by Stathopoulou (2011). In order to use this data more efficiently, the information in this format was edited, markers were renamed and reduced, and the frame rate was also reduced. Thanks to all this, MoCap data became compatible with parametric modeling, making it possible to visualize and manipulate the geometry of motion. For the creation of the parametric model, Grasshopper integrated with the software Rhinoceros was preferred. The obtained model was then applied to a playscape and a skate park for children (Figure 2.16). Stathopoulou (2011) stated that the architecture of these spaces does not have definite patterns about how to use them. Instead, it encourages children to use their imaginations and allows them to create programmatic uses of these structures on their own.

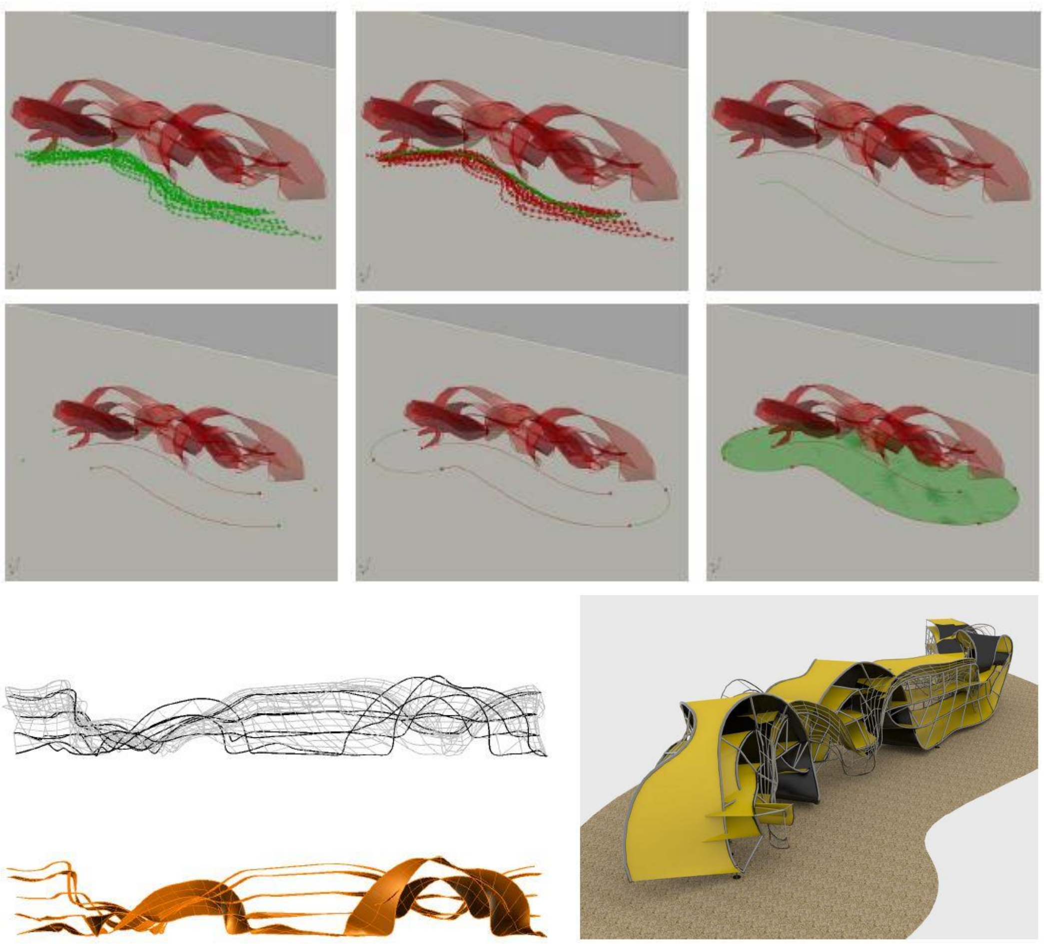


Figure 2.16. The Parametric Process of Turning Movement Data into a Playscape (Stathopoulou, 2011)

Kırkan and Çağdaş (2019) brought a different perspective to the subject of generating forms through movement. The main focus of their research was on turning movement data of dance performances into dynamic spaces which interact with the user’s movements. Accordingly, the body movements of a group of dancers were captured via the optical MoCap system and transferred to the computational environment. Kinect, Quokka, and Grasshopper interfaces were used in this process. The traces of the movements were converted first into a surface, then this surface was divided into grids, and lastly, spheres were placed at the corners of the grids (Figure 2.17). Thanks to a developed script within Grasshopper, the size of these spheres can change according to the user's distance to these spheres, and the ones reaching the maximum size remain constant. In other words, the designed interactive dynamic forms can react to the motion changes simultaneously and reshape their forms (Figure 2.18).

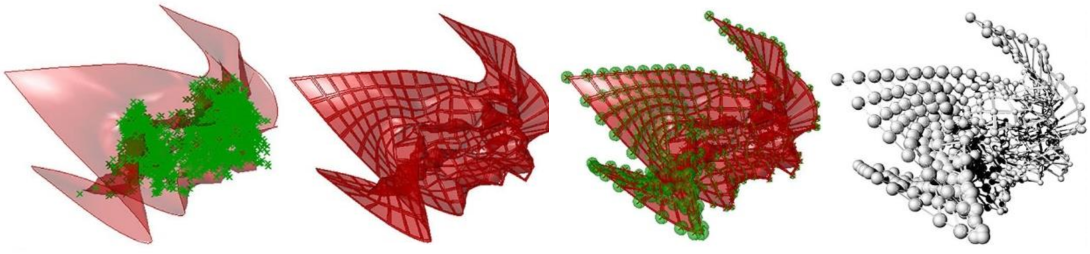


Figure 2.17. The Process of Generating an Interactive Form out of a Dance Performance in the Software Rhinoceros (Kırkan & Çağdaş, 2019)

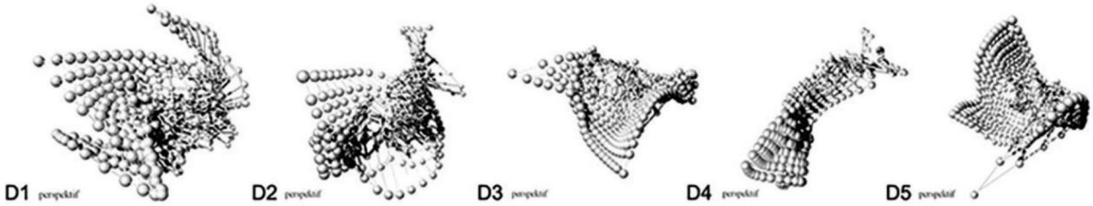


Figure 2.18. The Interactive Forms Created from the Movements of Five Different Dancers (Kırkan & Çağdaş, 2019)

Turning dance performances into dynamic spaces which interact with the users' movements was also experimented with by Metabody. Metabody is a European project participated by 35 institutions from 16 countries. It began in 2013 to develop new forms of interactive and intelligent architecture by utilizing the frameworks and technologies of all artistic disciplines, such as music, dance, architecture, visual arts, and performance art, in order to promote creativity in all its forms. One of the forms created through this project by Metatopia Studio can be seen in Figure 2.19. It consists of flexible and dynamic semi-transparent structures, called 'flexinamic', body sensors, and interactive lights and sounds. These structures are attached to the performers' bodies and move with the performers. They have openings that allow also the audience to enter. The created space can transform with the movement of bodies in it (Metatopia Studio, 2014).

Figure 2.19. The Interactive and Performative Environment Metatopia/Metabody (Metatopia Studio, 2014)

2.2 Personal Space in Architecture

In the research of Namazian and Mehdipour (2013), it is stated that psychologists express personal space as an invisible bubble. Humans need this hypothetical spatial bubble to regulate their privacy when interacting with each other in an environment. Many factors determine the size of this bubble. One of these factors is the type of relationship between those interacting with each other. For instance, the distance between business partners is different from the distance between friends. Or, while a person avoids close range in interacting with a stranger, the same person may want to be close to loved ones. Therefore, personal space is a dynamic process.

The distance between interacting people also varies depending on cultural aspects and individual personalities that influence people's thinking, perception, and behavior. According to Lewis Mumford's definition, culture is the learned behaviors and the results of these behaviors in line with the transfer of the common behaviors of a particular society among the members (Namazian & Mehdipour, 2013). The culture in which an individual grows up has a great influence on the shaping of his personality, and people with different personalities react differently to each other and to the physical environment they live in. For instance, a behavior that seems normal to one person may be perceived as annoying by another (Heiner, 2012). Therefore, the size of the personal space needed may differ from culture to culture and from individual to individual.

The conditions of the environment where the interaction takes place are also factors in determining the size of the personal space (Heiner, 2012). For instance, in a large room, people tend to keep less distance between each other than in a small room. Or a place with an unobstructed view, like a skyscraper, creates the feeling of a large room, so people tend to keep less distance from each other. Similarly, people need less personal space if a space has an open or a high ceiling. Where people are situated in space is also an important factor. For instance, people in the middle of the room need less personal space than people in the corners. In addition to these, unlike the physical conditions of the environment, the strangeness of a space that is entered for the first time can cause people to need more personal space than a familiar one (Heiner, 2012).

While discussing the environment, the following inference can be made at this point. The environment affects people not only with its physical conditions but also with its social conditions. As Namazian and Mehdipour (2013) stated, designing an environment is not just about designing a container that allows human activities. Special layouts suitable for the activity patterns of the users should also be designed, and their psychological aspects should be taken into account. As Winston Churchill stated, “We shape our buildings_thereafter they shape us.” (Boradkar, 2010). Hence, an architectural space should meet users' physical and psychological needs.

In order to achieve this, architectural designers need to focus on human movement patterns, arrangements that allow interaction among people, the usability of spaces for privacy needed, and appropriate physical dimensions (Altman, 1975; as cited in Namazian & Mehdipour, 2013). Also, they need to be aware that these may vary according to users from different social groups. Therefore, the conditions of an environment to be designed should allow users from different social groups to interact with each other while also meeting everyone's personal space preferences.

Regarding the architectural design of personal space, the aforementioned hypothetical spatial bubble concept can be taken as a basis. However, the architectural counterpart of this bubble should not be to provide privacy by simply surrounding it with walls. A flexible and adaptable design should be made in which the users can personalize the space in line with their physical and social needs.

An example of a personal space designed with this approach is the Sky Gazing Tower project (Figure 2.20). This project is an open space installation designed as part of the LA Design Festival 2019 and aims to offer personal space to people living in crowded cities (Goti & Morse, 2021). Disorders such as stress, social anxiety, and agoraphobia are common in crowded cities. It is aimed that when people experience such difficulties, they can enter the Sky Gazing Tower and use its VR interface to create the boundaries of their own personal spaces and relax by looking at the sky. This personal space is composed of a steel frame and translucent vinyl membrane strips suspended from this frame. Therefore, there is no complete disconnection between the external and the internal environment. It is low-cost to manufacture and easy to transport and assemble. In the VR environment, there is a virtual structure of this installation in a simulated urban environment. The parameters such as the material, color, size, frequency, and height of the strips can be adjusted by the users in this virtual environment. So, the place can be personalized (Goti & Morse, 2021).

Figure 2.20. Sky Gazing Tower Installed on Site and its VR Interface (Goti & Morse, 2021)

Another example of a personal space that can be personalized is the Transformable M-Velope designed by Michael Jantzen (Figure 2.21). It is a built project where people can go and rest their minds and souls (Berrones, 2007). Thanks to its hinged panels, people can create the openings they want in their personal spaces according to their own preferences. The structure can transform into different forms. It can be easily transported and installed as it is lightweight and requires no foundation. Benches with backrests inside allow eight people to sit comfortably, but multiple M-velopes can be connected together if more space is needed (Berrones, 2007).

Figure 2.21. Transformable M-Velope by Michael Jantzen (Berrones, 2007)

Another design by Michael Jantzen, where users can manipulate the design according to their wishes, is the Interactive Transformable Plaza (Figure 2.22). It is a conceptual proposal designed for open spaces (McQuarrie, 2014). In its unmanipulated form, it initially looks like a flat wooden platform. But it actually consists of planks hinged together. Attached to the short sides of this rectangular platform, there are nine stanchions topped with boat winches. By cranking any of these winches, people can lift different sections of the platform upwards to form an A-shape. There are eighteen sections in total; each differs in terms of width and height. If a person is detected on the platform by means of sensors, the movement of the sections stops for security reasons (McQuarrie, 2014). Thanks to this transformable structure, each different environment can meet the different personal space needs of people, and at the same time, different combinations of the platform allow different levels of interaction among people.

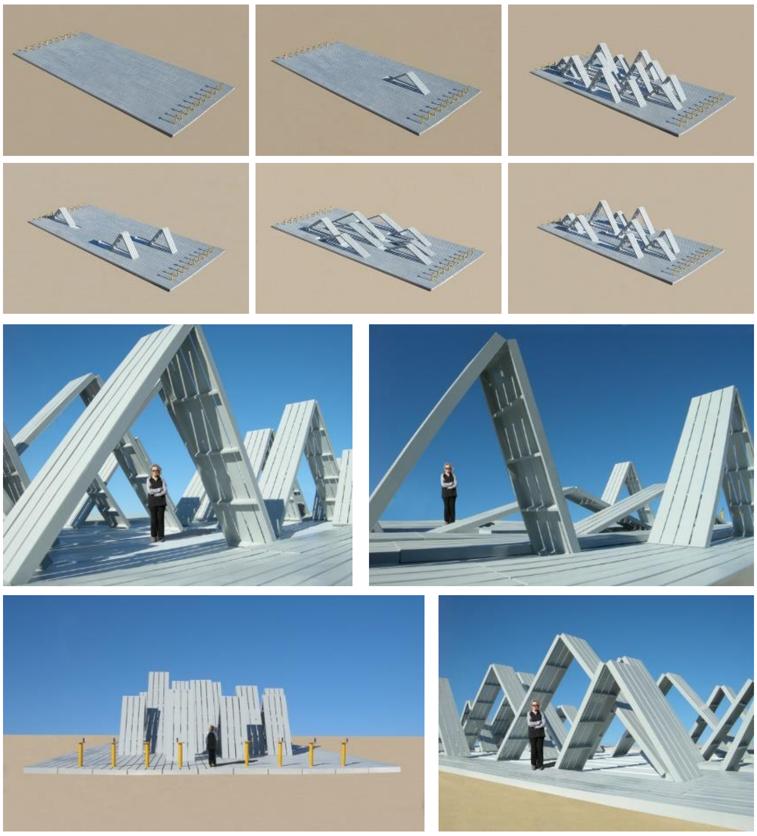


Figure 2.22. The Interactive Transformable Plaza by Michael Jantzen (McQuarrie, 2014)

While designing personal spaces, it is necessary to create spaces by considering both the physical and social needs of the users. At this point, it is important to understand both proxemics and ergonomics. While ergonomics focuses on how people can fit into their environment, proxemics deals with the social aspect of space. They are examined in detail in the following sections.

2.2.1 Personal Space from a Proxemic Perspective

The term "proxemics" was first used by anthropologist Edward T. Hall in his book The Hidden Dimension. It studies the way people organize the spaces and distances they put between each other in public and private, which differ between cultures (Hall, 1990). For instance, it deals with questions such as at what distance are people intimate, where their personal spaces end, what can be the distance for a good conversation among them, why the big round tables are sometimes so bad, how close people's desks should be in an office to encourage collaboration among them without making them feel jammed together, and why do people tend to whisper under the vaulted ceilings of a cathedral while they confess in a tiny box (Figure 2.23).

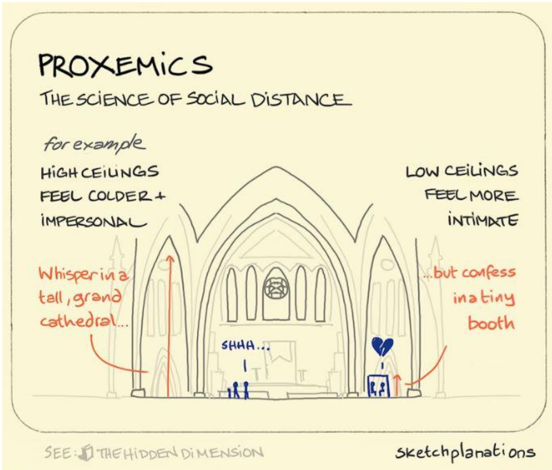


Figure 2.23. A Sketch Showing Different Proxemic Behaviors Under Tall and Low Ceilings (Hey, n.d.)

Namazian and Mehdipour (2013) stated that culture affects people's perceptions, cognitive representations, and behaviors. Therefore, people from different cultures experience architectural and urban environments differently. Even the environments might have been molded by people from different cultures (Hall, 1990). In order to meet the changing needs resulting from the different experiences of users, user control should be increased over the planned environments. Designers should utilize adaptable and participatory design solutions enabling users to regulate their privacy. In order to do that, it is necessary to understand the requirements of proxemics well.

According to Hall (1990), there are three aspects of proxemics. The first two are fixed-feature space (unmoving boundaries) and semifixed-feature space (moving arrangements), which are relevant to how people structure space. The last one is informal space, which is about the distances people use to interact with others. Each of these aspects is investigated separately in the following sections.

2.2.1.1 Fixed-Feature Space

Spaces formed by planning the activities of people with a consistent, uniform, or predictable arrangement are called fixed-feature spaces. It is a basic way of planning village, town, or city layouts such as the French radiating star, the Roman grid, the European naming the lines, the Japanese naming the intersecting points instead of the streets, and the American sameness of suburbia. Also, the internal layouts of buildings, such as the spatial organization of the Western house (there are special rooms for different functions such as preparing food, eating, resting, and socializing), can be given as an example of fixed-feature spaces. Size, shape, arrangement, and placement are particularly important fixed-feature elements in internal planning (Hall, 1990).

Fixed-feature space is not created solely by the design decisions of architects or planners and is not necessarily experienced as such by users. Users also bring with them the internalization of the fixed-featured space they learned in their early life. For instance, as stated by Hall (1990), the balconies of some of the buildings designed by Le Corbusier for the planned city of Chandigarh, India, were walled up and turned into kitchens by the users, because they wanted to use the space as they learned and got used to. As another example, Arabs feel depressed if they are not in large rooms with high ceilings. Therefore, they struggle to live and work in the gigantic apartments and office buildings of America as there are small rooms with low ceilings and no view or lack of privacy.

2.2.1.2 Semifixed-Feature Space

In semifixed-feature space, there are elements that can be moved and changed depending on the activities of people. Physician Humphry Osmond and psychologist

Robert Sommer conducted the first research to reveal the relationship between different arrangements of semifixed-features and how humans behave differently in these settings. The research was conducted in a hospital in Saskatchewan, Canada (Hall, 1990).

Before the research, Osmond had realized that most of the spaces in the hospital tend to keep people apart (which he called sociofugal spaces, figure 2.24.a) rather than bringing them together (which he called sociopetal spaces, figure 2.24.b). He also noticed that patients were talking to each other less often despite their long stay in the hospital ward, where everything was new, clean, and cheerfully coloured. Accordingly, together with Sommer, he conducted several experiments to demonstrate the effects of furniture on conversation.

As a result, they concluded that sociofugal spaces discourage conversation among people as the furniture arrangements in them are formal and fixed in rows. On the other hand, sociopetal spaces encourage interaction as the furniture can be arranged at different distances and orientations. However, discouragement and encouragement of these spaces can differ from culture to culture. There are no universal applications. The important thing is to provide flexible design solutions.

(a) spaces like railway waiting rooms (b) spaces like a French sidewalk cafe

Figure 2.24. (a) Sociofugal Space, (b) Sociopetal Space (Hall, 1990)

According to Hall (1990), culture even affects whether a space is fixed or semifixed. For example, in America, the walls of a house are considered as fixed elements because Americans tend to move from one room to another for different functions. On the other hand, in Japan, the walls are considered semifixed because, in Japanese homes, the walls can be moved so that each room can be used for more than one function. Thus, people do not need to change spots. Briefly, the way people treat space is diverse.

2.2.1.3 Informal Space

Informal space is the most important aspect of proxemics because it deals with the distances people use outside of awareness in interacting with others. As mentioned before, these distances vary depending on the cultural aspects and individual personalities that affect people's thinking, perception, and behavior (Namazian & Mehdipour, 2013). In this context, it is also necessary to draw attention to the situational personalities Hall (1990) mentioned in his book 'The Hidden Dimension'. As he stated, each person has different individual personality structures, such as extroverts, introverts, egalitarian and authoritarian, as well as more than one situational personality structure. The indicator of people's situational personalities is how they sense others as close or distant and then react to them in informal encounters (intimate, personal, social, and public). For instance, people who have not developed the social aspect of their personalities may exhibit timid attitudes in social environments. Or other people may have problems in intimate and personal zones and may not tolerate being close to others.

Although each person may sense different distances in different types of encounters, there are generalizations made in the light of proxemic observations. The informal distance classification made according to these generalizations consists of four zones which are intimate, personal, social, and public (Hall, 1990) (Figure 2.25). Each of these zones is reviewed in the following.

i. Intimate Distance

It is the distance where the other person's details can be seen the most. For instance, the distance between partners is intimate. However, if foreigners enter this zone, physical discomfort is experienced. Bodily contact with strangers is considered taboo. For example, it is very likely to be observed in a crowded elevator (Hall, 1990).

ii. Personal Distance

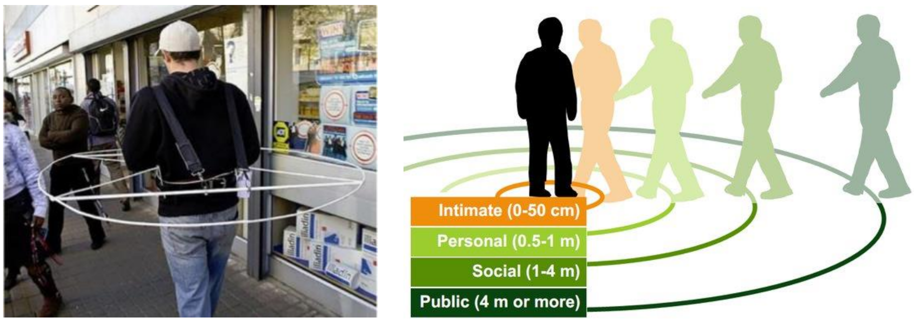
It is the distance to keep someone at arm's length. It can also be thought of as a protective bubble surrounding human. For instance, the distance between friends is personal (Hall, 1990).

iii. Social Distance

It is the distance between strangers in public areas. Also, impersonal business takes place in this zone. For instance, the distance between people in a formal meeting is social. Visual details on other people's faces cannot be perceived at this distance, and there is no human contact unless specifically intended (Hall, 1990).

iv. Public Distance

It is the distance between people who do not have direct relationships (Hall, 1990).



(a) (b)

Figure 2.25. (a) Personal Space Protector (Destro, 2009), (b) Hall’s Informal Distance Classification (Marquardt & Greenberg, 2011)

If the distance that a person has determined to keep between the people he/she interacts with is exceeded by the other party, this person starts to feel uncomfortable. This situation is referred to as a proxemic problem. For instance, being too close to strangers on a bus, elevator, or queue creates a feeling of discomfort. In order to prevent this, designs should be made within the framework of proxemic zones.

Moreover, Hall (1990) points out that which zone is used in which type of relationship may vary according to different ethnic origins, cultures, and genders. The intimate zone of one culture may be a personal, perhaps even a public zone for another culture. For instance, it is not a problem for Arabs to stay close together, while Japanese or Norwegians want to stay more than an arm's length away from each other. Also, French people have a tendency to be closely packed together, which is not appreciated by Americans, northern Europeans, and the British (Hall, 1990). Furthermore, behaviors in the same zone also differ from culture to culture. For example, Americans tend to wait facing each other's back in an elevator while Europeans wait face to face (Figure 2.26).

Figure 2.26. An Example of Proxemic Behavior that Varies from Culture to Culture (Anonymous, nd.)

2.2.2 Personal Space from an Ergonomic Perspective

Ergonomics is concerned with how and where the work is done, by whom, over what period, and the psychological effects of the work done. In other words, it is 'the science of work' in general. As a word, ergonomics is formed from a combination of the Greek words 'ergos' meaning thing to be done to live, and 'nomos' meaning natural law (Pheasant & Haslegrave, 2018).

According to Pheasant and Haslegrave (2018), an ergonomic design should be user-centered. For this, the product (environment, system, or object) should be designed in accordance with the physical and mental characteristics of the users and the task they will do, i.e., getting the best match between the task, the product, and the user is key to an ergonomic design (Figure 2.27). In order to achieve this, ease of use, functional efficiency, comfort, quality of performance, and health and safety must be considered with equal importance.

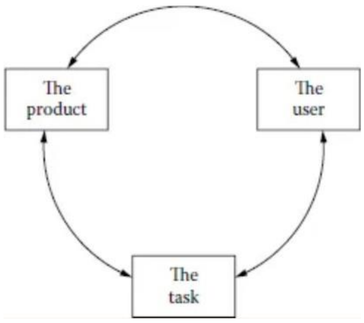


Figure 2.27. User-Centered Design (Pheasant & Haslegrave, 2018)

For a user-centered design, measurements of people with different body sizes, proportions, shapes, flexibility, strength, and mobility should be taken into account. Anthropometry, which is a scientific study dealing with these variabilities, therefore constitutes an important part of ergonomics. Most design problems concern the general user population. There may be cases where designs for single users should be made, but in general, it is useful to consider that designs should be usable by the majority of the population. For this, they should be adjustable or produced in various sizes (Pheasant & Haslegrave, 2018). At this point, the information needed to determine the dimensions of a design that can meet everyone's wishes and where adjustability is needed in this design are firstly, the anthropometric data of the user population, secondly, what kind of constraints this data can bring to the design, and thirdly, how these constraints can be met in the design of space. These are discussed below in separate subheadings.

2.2.2.1 Anthropometry Data of the Human Body

Regarding the first information, there are two types of anthropometric data: static anthropometry data and dynamic (functional) anthropometry data. Static anthropometry deals with the dimensions of people's fixed, standardized postures, while dynamic (functional) anthropometry deals with the dimensions of people in motion (Pheasant & Haslegrave, 2018). This part of the research focuses more on dynamic anthropometry data.

One person can do the same task differently than another person. The way a task is done can vary even for the same person. Therefore, it is often not possible to measure dynamic data with 100% accuracy compared to static data. However, it is useful to use this data for functional space requirements (Pheasant & Haslegrave, 2018).

In a study conducted by Turkish Statistical Institute (TÜIK) in 2004-2005, the anthropometric data of Turkish people were revealed (Güleç et al., 2009). The body measurements of men and women are given in Tables 2.1 and 2.2.

Table 2.1 The Anthropometric Data of Turkish Men (Reproduced from Güleç et al., 2009)

	Avg.	SD.	5.	25.	50.	75.	95.
Height (cm)	168.88	6.76	158.30	164.20	168.70	173.60	179.85
Weight (kg)	74.74	12.32	55.90	66.00	73.65	82.63	96.80
Bust Height (mm)	887.27	36.38	825.55	863.00	887.00	912.00	946.00
Waist Height (mm)	964.20	56.57	867.55	931.75	967.00	1002.00	1050.00
Knee Height (mm)	522.99	27.36	480.00	504.75	522.00	542.00	568.00
Lower Leg Height (mm)	483.85	44.90	415.00	450.00	482.00	514.00	562.00
Head Length (mm)	186.40	7.91	173.00	181.00	186.00	192.00	199.00
Full Arm Length (mm)	748.54	37.21	687.55	725.00	751.00	773.00	808.90
Upper Arm Length (mm)	353.11	23.73	312.00	339.00	354.00	367.00	390.00
Forearm Length (mm)	269.22	16.40	241.55	258.00	270.00	280.00	295.00
Hip-Knee Length (mm)	557.67	40.18	468.00	542.75	563.00	583.00	613.00
Upper Leg Length (mm)	475.03	41.74	417.55	447.00	470.00	495.00	562.00
Foot Length (mm)	261.48	13.08	242.55	254.00	261.00	270.00	282.00
Hand Length (mm)	195.54	10.46	178.55	189.00	196.00	202.00	212.45
Finger Length (mm)	106.74	7.06	94.00	102.00	107.00	111.00	118.00

Table 2.2 The Anthropometric Data of Turkish Women (Reproduced from Güleç et al., 2009)

	Avg.	SD.	**5.**	**25.**	**50.**	**75.**	**95.**
Height (cm)	155.03	5.93	147.10	154.73	161.35	168.88	177.40
Weight (kg)	67.12	14.17	50.21	61.13	69.70	79.58	95.30
Bust Height (mm)	820.74	35.52	775.05	817.00	855.00	888.00	935.00
Waist Height (mm)	869.14	50.11	804.00	864.00	913.00	970.00	1034.00
Knee Height (mm)	477.60	23.00	448.05	475.00	498.00	524.00	558.00
Lower Leg Height (mm)	431.77	33.66	391.00	425.00	451.00	488.00	543.00
Head Length (mm)	176.77	7.14	168.00	175.00	181.00	188.00	197.00
Full Arm Length (mm)	683.68	39.80	633.00	680.25	716.00	755.00	794.95
Upper Arm Length (mm)	325.72	28.43	289.00	321.00	341.00	360.00	384.00
Forearm Length (mm)	237.17	16.95	217.00	236.00	253.00	271.00	289.00
Hip-Knee Length (mm)	548.36	29.59	490.10	534.00	555.00	575.00	605.00
Upper Leg Length (mm)	464.84	32.21	416.00	445.00	467.00	488.00	540.00
Foot Length (mm)	236.19	12.28	221.00	235.00	249.00	262.00	278.00
Hand Length (mm)	180.27	10.62	167.00	179.00	188.00	197.00	209.00
Finger Length (mm)	93.26	8.10	83.00	93.00	100.00	108.00	115.95

What kind of constraints all these data may impose on designs constitutes the second information necessary to meet the general user needs and are examined in detail in the next section.

2.2.2.2 The Constraints of Anthropometrics

The constraints of anthropometrics occur depending on the task being performed and the physical or mental characteristics of the users. In the design and layout of the spaces, it is an important decision on which people's characteristics will be taken as a basis in the user population with varying physical or mental characteristics. For instance, when designing based on average body measurements, design may be useless for people who are above or below the average. Instead, according to Pheasant and Haslegrave (2018), the 'limiting user' in the human population should be taken as a basis for determining the appropriate dimensions of the design because they stated that the limiting user imposes the most severe constraints on design.

Accordingly, when the dimensions of the relevant body parts of all population members are distributed, it should be considered which tail of the distribution limits the design more to the rest of the users. In such cases called one-way constraints, the limiting user, for instance, can be either a small person or a bulky person. In a more problematic design problem, even both tails of the distribution can impose severe constraints, which are called two-way constraints. So, there are limiting users in both tails (Pheasant & Haslegrave, 2018). In such cases, the design requires adjustability so that it can fit everyone.

These will be further investigated under the four main constraints of anthropometrics which are clearance, reach, posture, and strength, specified by Pheasant and Haslegrave (2018).

i. Clearance

Clearance design constraints are related to providing adequate spaces to perform a task comfortably, such as adequate access, circulation space, headroom, legroom, and elbow room. It is necessary to start solving a clearance problem by thinking of a bulky person as a limiting user because the requirements of that space for the remaining members of the population who have smaller dimensions will necessarily be met. Therefore, clearance constraints fall under one-way constraints determining the minimum acceptable dimensions of a person having a relatively larger body size (Pheasant & Haslegrave, 2018).

Some of the clearance dimensions necessary to be considered in the design of spaces are given in Table 2.3.

Table 2.3 The Dimensions (in Millimeters) in Various Clearance Positions (Pheasant & Haslegrave, 2018)

		Men				Women			
	Dimension	5th %ile	50th %ile	95th %ile	SD	5th %ile	50th %ile	95th %ile	SD
1.	Maximum body breadth	480	530	580	30	355	420	485	40
2.	Maximum body depth	255	290	330	22	225	275	325	30
3.	Kneeling height	1210	1295	1380	51	1130	1205	1285	45
4.	Kneeling leg length	620	685	750	40	575	630	685	32
5.	Crawling height	655	715	775	37	605	660	715	33
6.	Crawling length	1215	1340	1465	75	1130	1240	1350	66
7.	Buttock–heel length	985	1070	1160	53	875	965	1055	55

ii. Reach

Reach design constraints are related to providing comfortable access to things. For instance, placing a display screen at an appropriate distance for reading a text comfortably or an appropriate seat height to easily access items is a matter of reach. It is necessary to start solving a reach problem by thinking of a small person as a limiting user because the requirements of that space for the remaining members of the population who have larger dimensions will necessarily be met. Therefore, reach constraints fall under one-way constraints determining the maximum acceptable dimensions of a small person having a relatively smaller body size (Pheasant & Haslegrave, 2018).

iii. Posture

Postural design constraints are related to creating the environment and equipment to suit the attitude of the user's body for the task to be performed. More than one dimension of a place can affect the user's posture; therefore, postural design problems are more complex than clearance and reach problems. Thus, different users might have different needs regarding their postures. For this reason, postural constraints fall under two-way constraints determining both the minimum and the maximum acceptable dimensions (Pheasant & Haslegrave, 2018).

iv. Strength

Strength design constraints are related to the force that needs to be applied in a physical task. It is necessary to start solving a strength problem by thinking of a weak person as a limiting user because the remaining members of the population who are stronger will necessarily be able to apply the required level of force to perform the same task. Therefore, strength constraints also fall under one-way constraints as clearance and reach. On the other hand, the level of force arranged based on weak people may cause an accidental operation of control by strong people. For this reason, in some cases, both tails of the strength distribution may need to be considered in the design; hence, two-way constraints might also apply (Pheasant & Haslegrave, 2018).

The third information required to meet the general user needs is about how all these constraints can be met, and it is examined in detail in the next section.

2.2.2.3 Application of Anthropometry in the Design of Space

Among the four constraints of anthropometry, clearance and reach have a greater impact on personal space design, the essence of which is to create a free space suitable for the psychological needs of individuals. Therefore, more emphasis is placed on the dimensional requirements of clearance and reach in this section.

The dimensional requirements of clearance affect movement and flow, density, and people's spatial experience and behavior. These are investigated under sub-headings.

i. Movement and Flow

In order to make arrangements according to the movement and flow of people in space, Fruin (1971) introduced the concept called body ellipse (Pheasant & Haslegrave, 2018). It is the first simple method to show the space requirements of the body of a standing person in the plan view. As seen in Figure 2.28, the ellipse was drawn according to the body depth and shoulder breadth dimensions of a male body based on human factors studies.

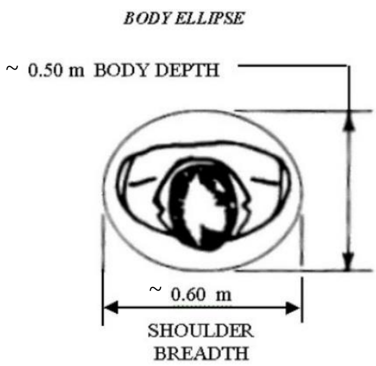


Figure 2.28. Fruin’s Human Body Ellipse in Plan View (Rouphail et al.,1998 as cited in Itami, 2002)

Besides the body ellipse, Pheasant and Haslegrave (2018) also added arm span and elbow room circles to the plan view to show the whole body's occupied space. In Figure 2.29, AS 95%ile m, AS 5%ile w, ER 95%ile m, and BE 95%ile m are the abbreviations of 95th percentile arm span in men, 5th percentile arm span in women, 95th percentile elbow room in men, and 95th percentile body ellipse in men, respectively. Thanks to this representation, the space requirements for clearance can be better analyzed.

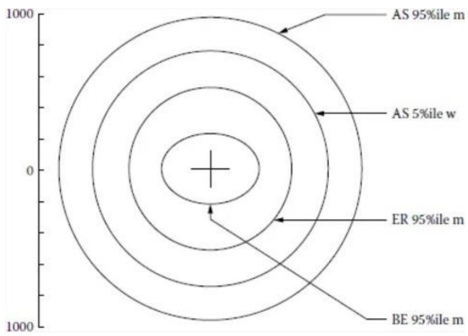


Figure 2.29. Analysis of the Space Requirements of a Standing Person from the Plan Plane, Dimensions are in Millimeters (Pheasant & Haslegrave, 2018)

ii. The Density of People Within a Space

Density has an important effect on the design of space in terms of clearance. In expressing density, Pheasant and Haslegrave (2018) considered the distances between people in space. Accordingly, the density level of space varies between a closely packed state where movement is not possible and, therefore, people feel uncomfortable and a state with free circulation (minimum 120 cm interpersonal spacing) where one person does not disturb another. The tolerance of people to these different density levels differs according to the environment, context, and duration. Designers should decide on the clearance dimensions in the space according to the density level they predict to occur in space. At this point, they may consider the minimum dimensions required for comfortable movement and flow of the users shared by Pheasant and Haslegrave (2018), given in Table 2.4.

Table 2.4 The Minimum Dimensions Required for Comfortable Movement and Flow of People, Dimensions are in Millimeters (Pheasant & Haslegrave, 2018)

Widths of Access	
One person walking normally	650 (600 restricted)
Two people passing or walking side by side	1350 (1200 restricted)
One person walking, another flattened against wall	1000 (900 restricted)
Two people passing crabwise (sideways)	900 (850 restricted)
Wheelchair user — minimum	750
Wheelchair user — reasonable	800
Wheelchair user — preferred	900

Passage between Obstacles	Normal	Crabwise (sideways)
Both obstacles greater than 1000 mm in height	600	400
One obstacle greater than 1000 mm in height, the other less	600	400
Both obstacles less than 1000 mm in height	550	350
Standing in line	450 per person	

Source: After Pheasant, S. T. (1987). *Ergonomics: Standards and Guidelines for Designers*, PP 7317, London: British Standards Institution.

iii. The Spatial Experience and Behavior of People – Personal Space

In addition to the concepts of movement, flow, and density, which take into account the space occupied by the human body, spatial experience and behavior of humans should also be considered in selecting appropriate clearance dimensions in space. In this context, it is necessary to investigate the concepts of territoriality and personal space.

Territoriality arises from people's attempts to define a space temporarily or permanently for their own private use (Pheasant & Haslegrave, 2018). At this point, the concept of personal space emerges, which is expressed as ‘portable territory’ by Sommer (1969; as cited in Pheasant & Haslegrave, 2018), as a ‘protective bubble’ by Hall (1990), or as ‘subjective feelings of territoriality’ by Longstaff (1996). It surrounds the human body everywhere and controls interactions with others within invisible boundaries. These invisible boundaries are divided into four spherical zones by Hall (1990), as mentioned before in Section 2.2.1.3. These are intimate, personal, social, and public (Figures 2.25 and 2.30). For a detailed explanation of each, it can be referred to the relevant section.

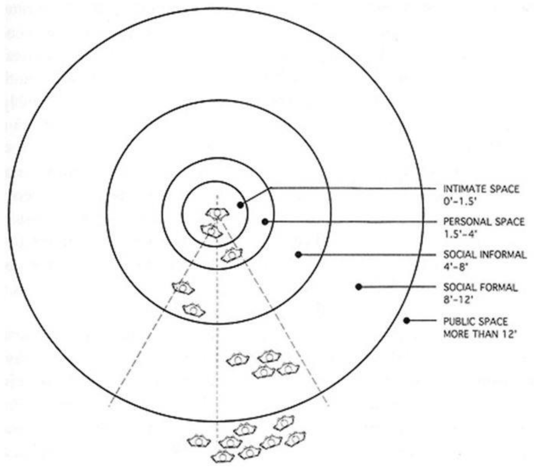


Figure 2.30. Proxemic Zones of Hall (Bingham-Hall & Cosgrave, 2019)

Additionally, these hypothetical boundaries do not necessarily have to be spherical, as Hall (1990) defined. For instance, Argelaguet et al. (2015) demonstrated personal space with an elliptical shape (Figure 2.31). Accordingly, the clearance distance of a person to an obstacle should be greater when positioned opposite to the obstacle and less when adjacent to the obstacle because people can tolerate others better side-by-side rather than face to face. This can also be seen in Figure 2.32.

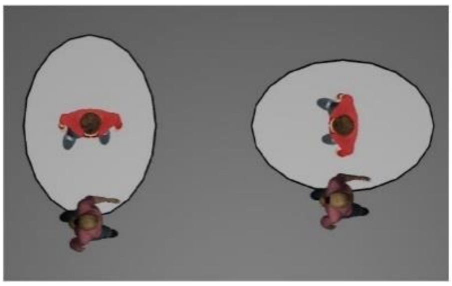


Figure 2.31. Elliptical Shaped Personal Space. The Clearance Distance Varies Depending on the Orientation to the Obstacle (Argelaguet et al., 2015)

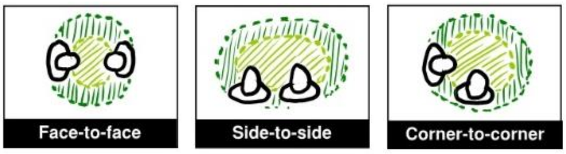


Figure 2.32. The Emerging Space Between Interacting People According to Their Orientation to Each Other (Marquardt, Hinckley & Greenberg, 2012)

When personal space is evaluated from a proxemic perspective, designing in accordance with the distances between interacting people comes to the fore. When it is evaluated in terms of ergonomics, it comes to the fore that the space directly around the person should be designed accordingly, depending on the work to be done. However, in both evaluations, the psychological factors that affect the spatial experience and behaviors of the person should also be taken into account because the environment affects people not only with its physical characteristics but also with the psychological reflections of these physical characteristics (Pheasant & Haslegrave, 2018). These psychological reflections are referred to by Hall (1990) as 'hidden dimensions'.

For instance, in determining the height of a room or an opening, both a human height to meet the physical needs of all users in the light of anthropometric data and an amount of overhead clearance to meet the psychological needs of the users are taken into account (Figure 2.33). People tend to feel uncomfortable in low-ceiling spaces, as it creates claustrophobic feelings. The continuity of a low height in the line of vision causes discomfort to people. If it appears that a place with a higher ceiling will be reached, they feel more comfortable.

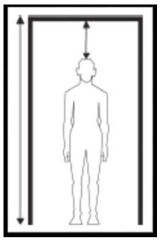
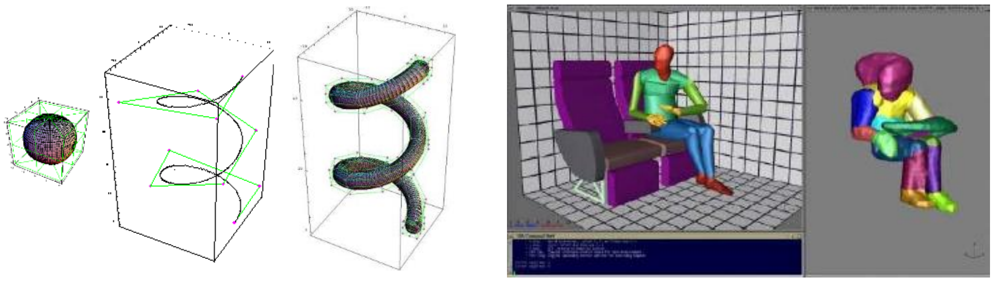


Figure 2.33. Determination of an Opening Height by Considering Human Height and Overhead Distance (Anonymous, 2019)

The size of the personal space that people need, both physically and psychologically, varies depending on many factors. In order to determine the ergonomically acceptable minimum personal space size, the 'human swept volume' method introduced by Troy and Guerin (2004) can be used (as cited in Yang et al., 2006; Pheasant & Haslegrave, 2018). Basically, a swept volume is the boundary surface covering the space used by an object in its activity, as can be seen in Figure 2.34.a. Accordingly, the human swept volume shows the activity pattern of the human body while performing an activity as shown in Figure 2.34.b. It is a useful method for space occupancy analysis.

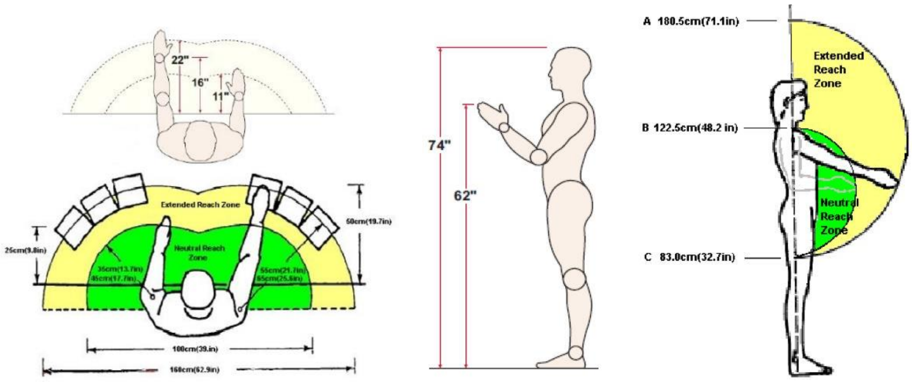


(a) (b)

Figure 2.34. Swept Volumes Created by a Solid Sphere Following a Path (a) and Human Movement in an Aircraft Seating Module (b) (Yang et al., 2006)

Besides clearance, reach also has a great impact on the design of personal space. The area where the human body can reach the maximum in terms of its movement capabilities in order to perform a task with optimum efficiency is called the 'reach envelope' (Pheasant & Haslegrave, 2018) (Figure 2.35). The horizontal zone of convenient reach is called the 'golden zone', and the vertical zone of convenient reach is called the 'strike zone' (Gobetto, 2014; Karasu, 2019) (Figure 2.36).

According to Pheasant and Haslegrave (2018), in any design problem related to "what to put where", the four principles developed by Ernest J. McCormick based on the arrangement of the various elements in relation to each other can be used. These four principles are importance, frequency of use, function, and sequence of use principles. They necessitate the most important or the most frequently used things to be in the most accessible places, things that have similar functions to be grouped together, and things used sequentially to be arranged in the same sequence. It would be beneficial to design the space within the reach envelope based on these principles.



(a) (b)

Figure 2.35. (a) Horizontal Reach Distances and Zones, (b) Vertical Reach Distances and Zones for Standing Positions (Weber, 2008)

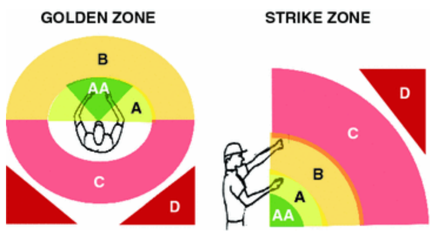


Figure 2.36. Golden Zone (Horizontal Ergonomic Zone) and Strike Zone (Vertical Ergonomic Zone) (Gobetto, 2014)

The reach envelope can also be demonstrated as a volume of space (Figure 2.37) which is called the ‘dynamic reach’ (Longstaff, 1996) or ‘kinetosphere’ (Pheasant & Haslegrave, 2018). Kinetosphere is a term coined by Dempster et al. (1959) to describe the range of space enclosing the motion of the hand and arm (Longstaff, 1996). In his studies, he produced three-dimensional models of the kinetospheres formed by recording the hand movements of the subjects (Figure 2.38).

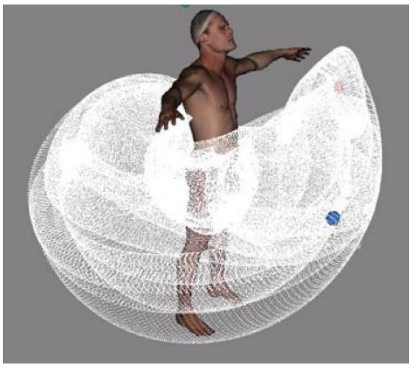


Figure 2.37. Human Reach Envelope as a Volume of Space (Movement of Toe with Respect to the Hip) (Yang & Abdel-Malek, 2008)

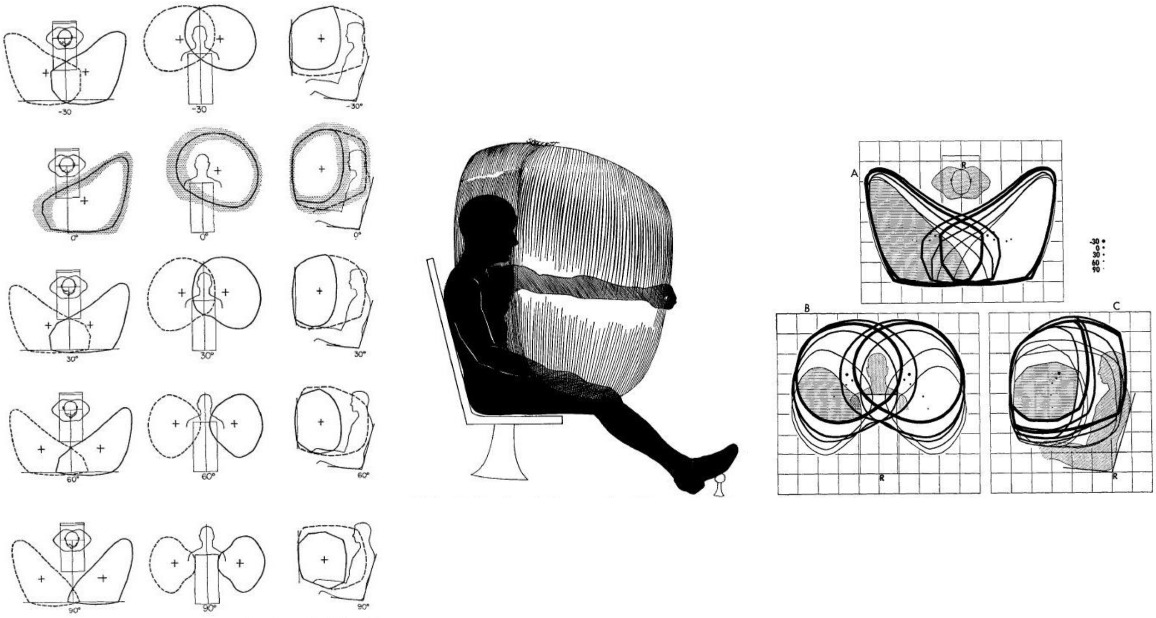


Figure 2.38. Several Demonstrations of Kinetospheres of an Average-Sized Subject (from left to right: Top, Front, and Left Views of Sections Passing Through the Centroids of the Kinetospheres, a Three-Dimensional Reconstruction, and Superimpositions of the Sections) (Dempster et al., 1959)

‘Kinesphere’, mentioned before in section 2.1.1, is a term similar to kinetosphere. The word ‘kinesphere’ was first used by Laban in dance studies. It is a virtual icosahedron that encompasses the entire space that an outstretched body can potentially reach (Stathopoulou, 2011). In this respect, it has a similar connotation to personal space. According to Longstaff (1996), personal space can be the same size as the kinesphere, if the personal distance extends to the furthest point that the limbs of the human body can reach. However, he also adds that personal space and the kinesphere differ from each other from a sociological point of view because Hall expresses personal distances as an extension of personalities rather than extensions of limbs. At this point, it is more appropriate to use Schick's (1990) term "psychological kinesphere" (as cited in Longstaff, 1996) to describe personal space.

2.3 Kinetic Architecture

This section focuses on reviewing existing publications about kinetic systems' progress, benefits, and movement principles.

Kinetics is a branch of mechanical science, and it examines dynamic systems together with the forces that cause and arise from motion. Taking advantage of this science in architectural structures designed by considering many environmental factors dates back many years. Depending on the technological, economic, and social conditions, the reasons for their use have diversified and developed over time.

Ramzy and Fayed (2011) analyzed the progress of kinetic systems in four phases:

- Primitive kinetic systems before the industrial revolution
- Premature kinetic systems after the industrial revolution
- 20th-century advanced kinetic systems
- Virtual reality age advanced kinetic systems

The effects of the above periods and the 4th industrial revolution period mentioned by Henriques et al. (2020) on kinetic architecture are analyzed under the titles of ancient and historic kinetic systems and robotic and intelligent kinetic systems.

2.3.1 Ancient and Historic Kinetic Systems

Adapting to the natural environment conditions has been of great importance in the architectural process that started with the search for housing to meet the shelter needs of human beings. Even at that time, human beings began to benefit from kinetics in architecture due to the movement's convenience. Based on Ramzy and Fayed's (2011) research, the first kinetic examples in architecture were seen in doors and windows. On the other hand, Fouad (2012) stated that kinetics extended to the cave and hut opening in his research and noted that pivots made of wood or stone and hinges made of leather were used. An example of kinetic structures used by ancient civilizations is the Asian Yurts (Figure 2.39), consisting of movable elements and components (Ilerisoy & Pekdemir-Basegmez, 2018). Kinetic systems not only provide security and weather protection but also facilitate transportation. With the help of moving bridges, both transport and defense were provided. One of the pioneers who invented these systems was Leonardo da Vinci (Figure 2.40) (Ilerisoy & Pekdemir-Basegmez, 2018). As a result, using ancient kinetic systems has varied depending on the requirements of the time and especially the conditions of nature.

Figure 2.39. Transportable and Deployable Asian Yurt (Ilerisoy & Pekdemir-Basegmez, 2018)

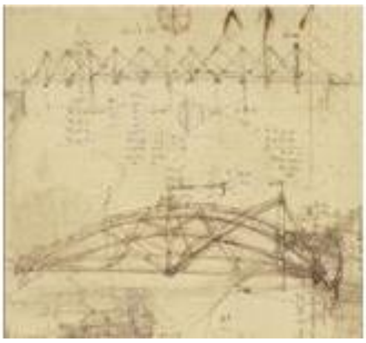


Figure 2.40. Movable Bridge Design of Leonardo da Vinci (Ilerisoy & Pekdemir-Basegmez, 2018)

Later on, kinetic systems driven by mechanical and hydraulic mechanisms began to be used in addition to the systems controlled manually by human or animal power (Ramzy & Fayed, 2011). Steam engines and electric motors that came with the industrial revolution brought a new dimension to kinetic architecture. Following these dynamic developments, the emergence of the futuristic movement has affected kinetic architecture (Ramzy & Fayed, 2011). This movement represents speed and motion and has emerged in architecture with dynamic forms.

Later examples of kinetic architecture took kinetics beyond form. Digital systems that emerged with the development of technology started to be used in architectural design processes. Motion techniques have been developed, making it possible to apply advanced kinetic systems to structures. Thanks to the advantages it provides, kinetic architecture has attracted a lot of attention both in the professional and academic fields after the 1980s (Ramzy & Fayed, 2011). Especially by architectural engineers Santiago Calatrava and Chuck Hoberman and the MIT Kinetic Design Group, kinetic architecture has been widely adopted. A lot of research has been done on it (Ramzy & Fayed, 2011). Their contributions to kinetic architecture will be mentioned in this study.

2.3.2 Robotic and Intelligent Kinetic Systems

Henriques et al. (2020) state that technological developments have led to radical changes in social and economic life after the Industrial Revolution. Because radical changes are also taking place today, the period which started at the end of the 20th century was expressed as "the 4th Industrial Revolution" in the research of Henriques et al. (2020). With the emergence of computational design, virtual and augmented realities, construction robotics, machine learning, sustainable parametric analysis, physical computing, and artificial intelligence, the methods and materials used in architectural design have gained a new dimension (Henriques et al., 2020). Kinetic systems have been supported by electronic and intelligent systems after they developed from manual to mechanical. Robots and remote-control systems with artificial intelligence have started to occur in the world of kinetic architecture (Ramzy & Fayed, 2011). The control mechanisms of these intelligent systems are computer-aided, and the kinetic movement is decided by interpreting environmental data. Therefore, intelligent kinetic solutions are more responsive and adaptive to changing factors.

Intelligent kinetic systems consist of many components. The structure is one of them, which is essential for the system to work as a whole. According to Fox and Yeh (2000), the structural solutions both affect the mechanical functions of the system, such as sliding and rotating, and affect the means of movement, such as chemical, magnetic, and pneumatic. Therefore, if advanced engineering and technology are utilized in the structure, the kinetic design will be lightweight, efficient, and flexible.

According to Fox and Yeh (2000), kinetic structures are divided into three categories. These are deployable, dynamic, and embedded kinetic structures (Figure 2.41). Deployable kinetic structures are transportable; hence they can serve in temporary locations. Examples include mobile pavilions or self-erected emergency shelters. Dynamic structures are modular systems that can move by themselves and can be applied to a building's components, such as door, window, and ceiling. Finally, embedded structures can control large scale systems by detecting variable environmental or human factors. They are used in intelligent kinetic systems and benefit from sensor technology. These structures can serve in fixed locations. They can obtain data from environmental or human factors with sensors' help, analyze them, and control the movement in this direction. They can even make interpretations in line with the collected data (Fox & Yeh, 2000).

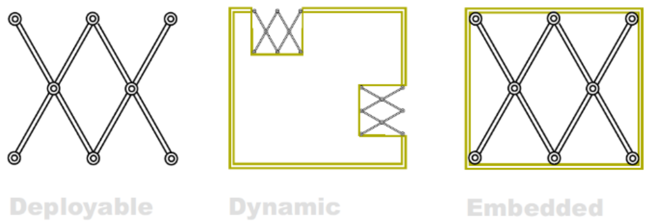


Figure 2.41. Diagram of General Kinetic Structures (Fox & Yeh, 2000)

2.3.3 Benefits of Kinetic Systems

According to Megahed (2016), the most important reasons for using kinetic systems are the increased need for comfort, flexibility, adaptability, and the desire to use natural resources more sparingly. In addition, kinetic architecture offers a wide variety of uses and creative solutions by using technology (Megahed, 2016). It both increases the functions of designs and adds fun to the use of this functionality (Megahed, 2016). Although they are seen as expensive systems, kinetic approaches can reduce buildings' expenses by providing energy efficiency after installation in buildings. The responsiveness, flexibility, adaptability, and transformability provided by kinetic systems are examined below in detail to understand why they are a suitable solution for adapting to dynamic conditions.

2.3.3.1 Responsiveness

Responsiveness provides buildings or building components with the adaptation to changes in their surroundings. These changes can occur in the users' activities or the internal or external environment. The reason and speed of the changes vary. Therefore, designing an adaptive built environment to respond to these changes is important.

According to Meagher (2015), every building has a certain degree of responsiveness. Even in static solutions, the most comfortable state can be achieved by opening and closing doors, windows, controlling the fans, and lowering blinds (Meagher, 2015). On the other hand, in kinetic architecture, buildings can respond to changes by dynamically modifying themselves using manual or automated kinetic systems. For instance, the first modern examples of kinetic buildings responding to human demands are the Fun Palace proposed in 1961 and the Interaction Center constructed in 1971 (Achten, 2019). These Cedric Price designs could change according to the needs of their users. However, as Achten (2019) states, apart from these exceptional examples, dynamism was only used indoors in the conventional buildings constructed later on until the 1980s, making them a static container and remaining passive. According to Achten (2019), this was due to the high cost of kinetic systems and the old times' technological insufficiency. Thanks to technological innovations after the 1980s, buildings began to be designed more dynamically. The building elements could move and change shape to be more flexible and adapt to the internal and external environments and users' changing needs (Achten, 2019).

2.3.3.2 Flexibility

Flexibility is an important design element for buildings as it can adapt to changing human and environmental factors. Islamoglu and Usta (2018) identified the ways to achieve flexibility in buildings in their research. To do that, they examined how the concept of flexibility emerged, how different architects from different periods defined this concept, and how they reflected it in their designs. After the First World War, radical changes were experienced in Europe, and new types of designs that could adapt to these changes in architecture began to be demanded. Therefore, the concept of flexibility started to be adopted (Islamoglu & Usta, 2018). Many architects have brought different definitions of flexibility since its emergence. Therefore, different architectural solutions have appeared. Islamoglu and Usta (2018) examined the definitions of flexibility that have changed over time to bring together all of them on a common ground (Table 2.5). As a result, they stated that flexibility is the ability to adapt to any change encountered in buildings with maximum capacity (Islamoglu & Usta, 2018).

Table 2.5 Definitions of Flexibility (Islamoglu & Usta, 2018)

Architect	Year	Definition
Weeks	1964	Uncertain architecture, when the building form is not tied to any function or capacity.
Collins	1965	A closed-circuit specified by the architect, specialized for multiple configurations.
Turan	1974	It is the capacity to provide reorganization and expansion by preserving the general arrangement of the structural components.
Tapan	1972	It is the ability of the same design unit to respond to different user needs without changing the building system and the possibility of using the same volumes for more than one function.
Atasoy	1973	It is the ability to meet changing needs with minimum effort based on variability.
Oxman	1975	Changeability, expansion, adaptability to changing conditions.
Yürekli	1983	It is the ability to change shape, return to its original shape, and adapt to constant change.
Maccreanor	1998	Flexibility is a designed idea that leads to the collapse of the traditional layout. Flexibility does not imply the necessity of endless change and breakdown of accepted formula.
Forty	2000	It is an illusion that gives architects future control of their buildings.
Friedman	2002	It is mobility and individual freedom.
Schnieder, Till	2007	It is the ability to provide physical changes in the structure.
Habraken	2008	Different spatial arrangements, adaptation, variety of use, and freedom.
Hertzberger	2009	It is a system of finding neutral solutions to specific problems.
Kronenburg	2011	It is the integrated attitude of the possible changes of the future with the current requirements and the freedom of use.

Later on, the flexibility applications were classified in the research of Islamoglu and Usta (2018), as seen in Table 2.6. These applications were divided into two groups: during the design process and while in use. The strategies of using different plan types, modularity, neutral areas, and adding/removing are the ones that can be applied in the buildings' design process. On the other hand, the strategies of multi-function use, mobility, and combining/dividing are the ones that can be utilized while in use of the buildings (Figure 2.42). Islamoglu and Usta (2018) stated that the first group's strategies are limited to the building system. Hence, it is necessary to use strategies from both groups to meet the changing needs through flexibility.

Table 2.6 Flexibility Approaches (Islamoglu & Usta, 2018)

Architect	Year	Flexibility Approach
Corbusier	1914	Free plan and free facade system
Taut	1920	Flexible plan forms that allow for versatile uses
Rietveld	1924	Arrangement and movable dividers around a core
Rohe	1927	Open plan system, add-on units, prefabrication systems and modulation system
Weeks	1960	Unfinished solutions, "indeterminacy."
Ripnen	1960	Circulation systems without walls, doors, having open areas where goods and people can move
Schulz	1963	Changing elements and their relationships
Lappart	1969	Possibility of development in land use and the carrier system does not prevent the changeability
Habraken	1972	Open plan system, and creating support and infill units in the structure
Yürekli	1983	Decisions regarding the construction technique and construction system
Duffy, Brand Leupen	1998 1994 2006	Layering the structure
Friedman	2002	Arrangement of subcomponents through growth and division
Stoa	2003	Multi-purpose common areas, different plan types, and secondary usage areas
Schneider, Till	2007	Soft and hard separation of building components
Hertzberger	2009	The structural system that supports the space setup that the user can shape and the multi-purpose use of the spaces
Kronenburg	2011	Adaptation, mobility, transformation, and interaction

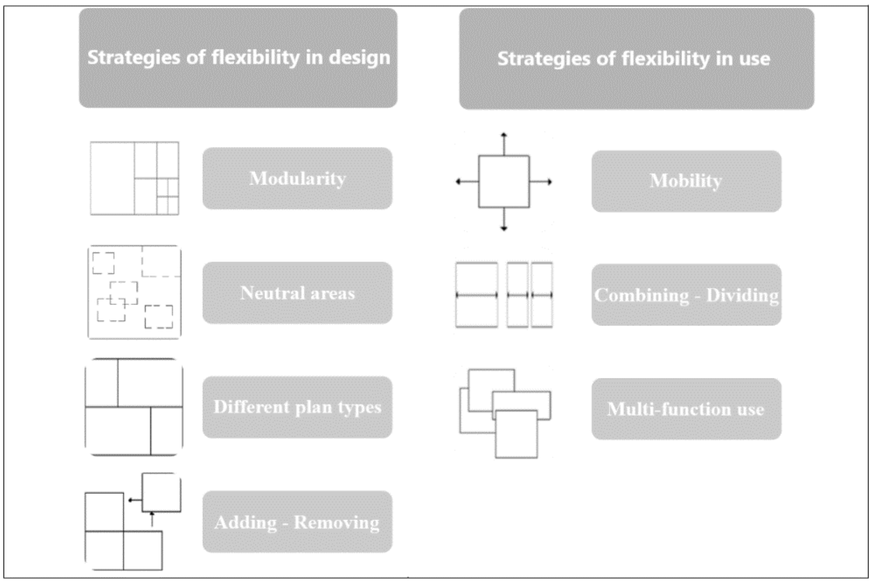


Figure 2.42. Strategies of Flexibility (Islamoglu & Usta, 2018)

2.3.3.3 Adaptability

According to Fouad (2012), adaptability is the flexibility of the space to face changing conditions. A building can be adaptive to changing human activity and environmental factors in different ways, such as using multi-use interior space or having a complete structure transformability. Fouad (2012) refers to Fox's book named 'Interactive Architecture' in investigating adaptability in living, working, entertainment, and public environments.

i. Living environments

Home-automation systems provide adaptability in living environments. These systems can control all the other systems available in the building, such as security, climate, lighting, and entertainment (Fouad, 2012). The designed living environments utilize ubiquitous control mechanisms that use multiple sensor-control device pairs to collect data and control the kinetic systems accordingly. In this way, the building can adapt to the changing demands. The inhabitants can even interact with each other or with the ones outside the home within a selected privacy level (Fouad, 2012).

ii. Working environments

The number of employees can change depending on the work to be done. Accordingly, the working spaces may require alterations to adapt to the changing needs. These alterations can be made by reconfiguring the space by moving/adding/removing furniture and dividers (Fouad, 2012). The movements can be controlled either manually or automated. The working environment can also be adaptive via interactive kinetic systems that control peripheral demands such as acoustics, lighting, view, and privacy.

iii. Entertainment environments

In general, entertainment environments need to have interactive elements such as facades, sculptures, fountains, and exhibits to attract people (Fouad, 2012). An adaptive place can increase interactivity as it allows the temporal elements to change within the environment flexibly. Entertainment environments can have different functions, such as amusement and education. With adaptive kinetic systems, it is even possible to provide both functions to increase interactivity. These environments can also be called 'edutainment' (Fouad, 2012).

iv. Public environments

The design of public environments requires the analysis of consumer trends instead of individual demands. These spaces also need to address social interaction (Fouad, 2012). Using adaptive kinetic systems can provide these spaces to fulfill the crowds' changing needs and interact with the public. For instance, a restaurant can reconfigure itself according to the different groups of people by analyzing their behaviors.

2.3.3.4 Transformability

Flexibility and adaptability can be defined as the ability to change physically and adapt to changing needs, respectively. Transformable systems provide both of these capabilities to the structures. The mechanisms and materials used in these systems vary and will be examined under six headings.

i. Flat Packed (Folding Mechanism)

Flat-packed mechanisms consist of auxiliary parts brought together with the help of hinges (Werner, 2013). The origami technique, the ancient art of paper folding, is often used to obtain an integrated foldable mechanism (Asefi & Aram, 2018). Tachi (2012) stated that this art has a wide usage area, from small-scale objects to large-scale architectural projects, thanks to its dynamic properties. Therefore, it is important for deployable and foldable structures. In Tachi's research dated 2011, the thick plates and hinges model expressed as "rigid-foldable origami" can be defined as the inclusion of origami in flat-packed systems. Rigid origami enables 3D forms to be obtained from 2D surfaces (Figure 2.43), and this transformation produces a synchronized motion (Tachi, 2012). By using the software Freeform Origami, Origamizer, and Rigid Origami Simulator developed by Tachi, it is possible to design and simulate folding mechanisms (Tachi, 2012).

Figure 2.43. Origami Application: Rigid Foldable Wall Materialized with Cloth and Cardboard (Tachi, 2011)

The kirigami technique is also used in flat-packed mechanisms; however, their use is not as common as origami. Kirigami is the ancient art of paper cutting. It also contains folds inside; in this respect, it is similar to origami. As stated in the research of Neville and Scarpa (2015), 3D cellular structures can be created from 2D surfaces by using the kirigami technique. An example of this is the open honeycomb engineering structure (Figure 2.44) obtained by applying kirigami techniques on flat surfaces made of composite or thermoplastic materials. The mechanical properties of these structures are very different from the traditional closed honeycomb. The kirigami application reduced the density and provided the structure variable stiffness and deployable capability (Neville & Scarpa, 2015). Cables were also used between adjacent rows to minimize the stress at the folding points (Neville & Scarpa, 2015).

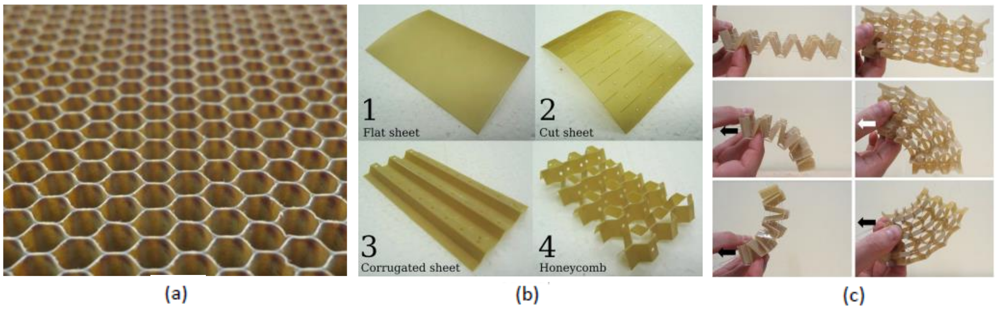


Figure 2.44. Kirigami Application, (a) Traditional Closed Honeycomb (Neville & Scarpa, 2015), (b) Manufacturing Process of Open Honeycomb, (c) Open Honeycomb Changing Shape by Pulling Cables (Neville, Scarpa & Pirrera, 2016)

ii. Pantograph (Scissors-like Mechanisms)

Pantograph, also known as a scissors-like mechanism, was developed by Architect Pinero in 1961 (Asefi & Aram, 2018). They have a modular structure; each module consists of two straight bars connected from their middle points using joints. This kinetic mechanism that shows expansion/retraction movement is obtained by connecting each bar in the module to the bars' endpoints in the other module.

It can be given a new dimension to these mechanisms by using angled bars instead of straight bars. By using bars with different angles and joints in different positions, a curvature can be obtained (Figure 2.45) (Asefi & Aram, 2018). Curved scissors mechanisms add more value to architectural designs. For example, architectural engineer Hoberman achieved a closed circle (Figure 2.46) by using multi-angulated bars in these mechanisms (Asefi & Aram, 2018). It has a similar working principle of an eye. Besides a circular shape, it is even possible to design a dome by using these systems.

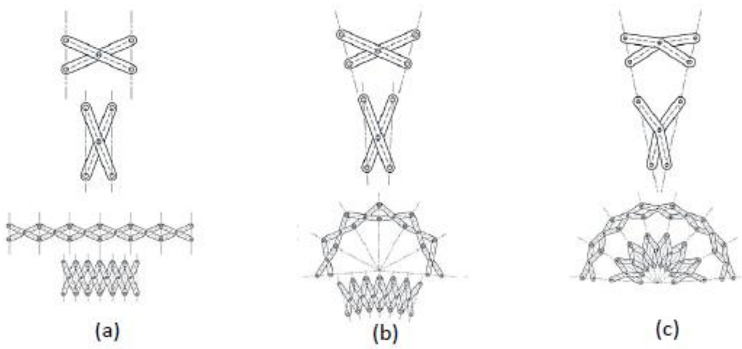


Figure 2.45. Scissor-like Mechanisms with (a) No Curvature, (b) Variable Curvature, (c) Constant Curvature (Asefi & Aram, 2018)

Figure 2.46. Hoberman Arch, A Scissor-like Curtain Designed for the 2002 Winter Olympics (Asefi & Aram, 2018)

iii. Membrane Systems

According to Werner (2013), membrane systems are a combination of a pre-stressed membrane and a structure. Membranes consist of woven yarns covered with fireproof, waterproof, and weather-resistant materials (Asefi & Aram, 2018). In addition, membranes are light, flexible, and foldable, and they provide self-cleaning. They also take up little space when folded. Therefore, it is frequently used internally and externally in transformable systems (Figure 2.47). Polyvinylchloride (PVC), polytetrafluoroethylene (PTFE), and ethylene tetrafluoroethylene (ETFE) are examples of materials used in membranes in transformable systems (Asefi & Aram, 2018).

Besides their advantages, membrane systems also have disadvantages. Membranes are very thin and vulnerable and therefore cause wear and tear and reduce the stability of the structure. It can also interrupt the kinetic movement (Asefi & Aram, 2018). Due to these problems, membranes are mostly used in temporary structures.

Figure 2.47. Membrane Systems, (a) Installed Internally (Asefi & Aram, 2018), (b) Installed Externally (Self-built during Foldable Pavilion Workshop, 2017)

iv. Pneumatics (Air Supported Systems)

Research by Zrim et al. (2017) referred to Otto and Trostel's book in describing the meaning of pneumatics. Accordingly, structures whose structural elements are temporarily loaded with force are called pneumatics. 'Pneuma' means breath of air in Greek (Zrim et al., 2017); hence pneumatics can also be called air-supported systems. Pneumatic systems mostly use membranes made of woven polyester (PES) yarns or glass fiber yarns. Woven PES yarns are partially or completely covered with polyvinylchloride (PVC), while glass fiber yarns are covered with polytetrafluoroethylene (PTFE) or silicone. Yarns add strength to the fabric and enable them to be used in the long term, and polymers enable the welding of fabric (Zrim et al., 2017).

Pneumatic structures can be erected quickly. Therefore, it is seen that they are mostly used in projects that start with a quick design decision and are expected to be completed in a short time. An example of this is the Ontario Celebration Zone pavilion (Figure 2.48), whose installation was completed within a week before the beginning of the Pan American Games (Jungjohann & Woodington, 2016).

Figure 2.48. Inflated Pneumatic Structure: Ontario Celebration Zone Pavilion (Jungjohann & Woodington, 2016)

v. Tensegrity (Cable-Bar Systems)

Mechanisms that consist of cables and bars in pure tension and pure compression are called tensegrity systems (Werner, 2013). They have a high level of transformability. The term pure tension and compression is used because the continuity of the cables is ensured throughout the system, and the bars never touch each other, as seen in Figure 2.49 (Bieniek, 2015). Cables are weak materials; however, they become resistant to external loads when they are pre-stressed and combined with strong bars. When a deforming load is applied to the system, the system can regain its equilibrium state, and this balance can only be disrupted if the cables are damaged or the bars are bent (Bieniek, 2015).

Cable-bar systems have also started to be used in architecture (Bieniek, 2015). However, their use is not yet common, and examples are seen in small-scale designs. The reason is that tensegrity systems have a difficult form-finding process. Furthermore, rigidity or flexibility can be achieved throughout the system with a suitable cable-bar combination. The method of this was explained in the research of Bieniek (2015) as follows: rigid tensegrity can be obtained by including all the elements in the specified configuration, and flexible tensegrity by loosening at least one of the bars. The transition from rigidity to flexibility is achieved with smooth movement. This kinetic motion gives the structure the ability to adapt to changing conditions, and in this respect, it is precious for kinetic architecture.

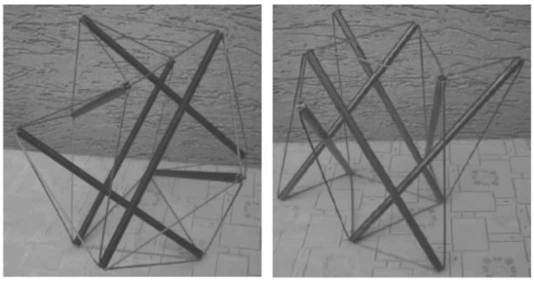


Figure 2.49. Examples of Pure Tensegrity: Six Bars in Different Composition with Cables (Bieniek, 2015)

vi. Pods or Capsules

Social and cultural changes and developments in construction technology have affected the housing typology; hence economically efficient minimal designs have gained importance. Examples of these are pods or capsules (Figure 2.50). Werner (2013) defined pods as skin supports and stated that they are mostly used in container structures in architecture. It connects to the exterior skin of another transformable system and can perform both rotation and translation movement. In Senk's (2013) research, compact, fully equipped mobile living units are called capsules. Its examples are mostly seen in hotels and prefabricated sanitary facilities. Thanks to the use of new materials, the entire volume or its components can move (Senk, 2013).

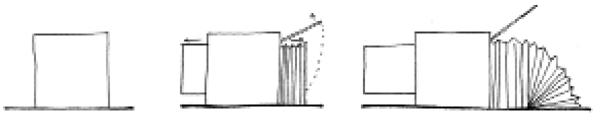


Figure 2.50. The Mechanism of Pods or Capsules (Werner, 2013)

2.3.4 Movement Principles of Kinetic Systems

The type of movement, construction systems, and control mechanisms vary in each structure depending on the desired function and the properties of the elements and components to be used. These are investigated further in detail.

2.3.4.1 Types of Movement

In order to understand the principles of movement in kinetic systems, the directions of motion are given in Figure 2.51. The term "degree of freedom" (DOF) is used in moving mechanisms. Its definition was given in the research of Qu, Fang & Guo (2015) by referring to Gogu as the "Number of independent coordinates needed to define the pose (position and orientation) of the moving platform." Accordingly, there are six directions of motion; three are rotational, and the others are linear. Each of them provides one DOF. A rotational movement can be seen around the x, y, and z axes, while linear movement, also called translation, can be seen parallel to the axes. The number of DOF of kinetic systems varies according to the mechanism that systems have.

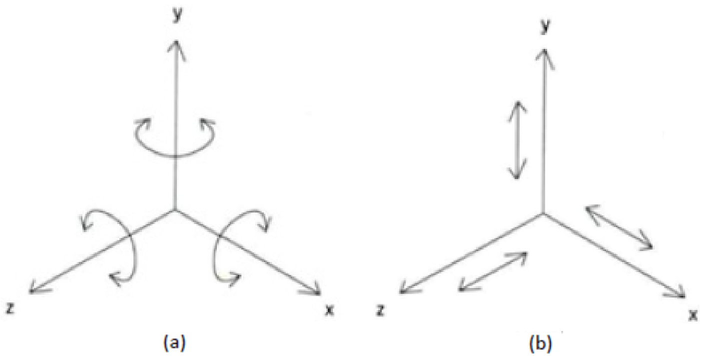


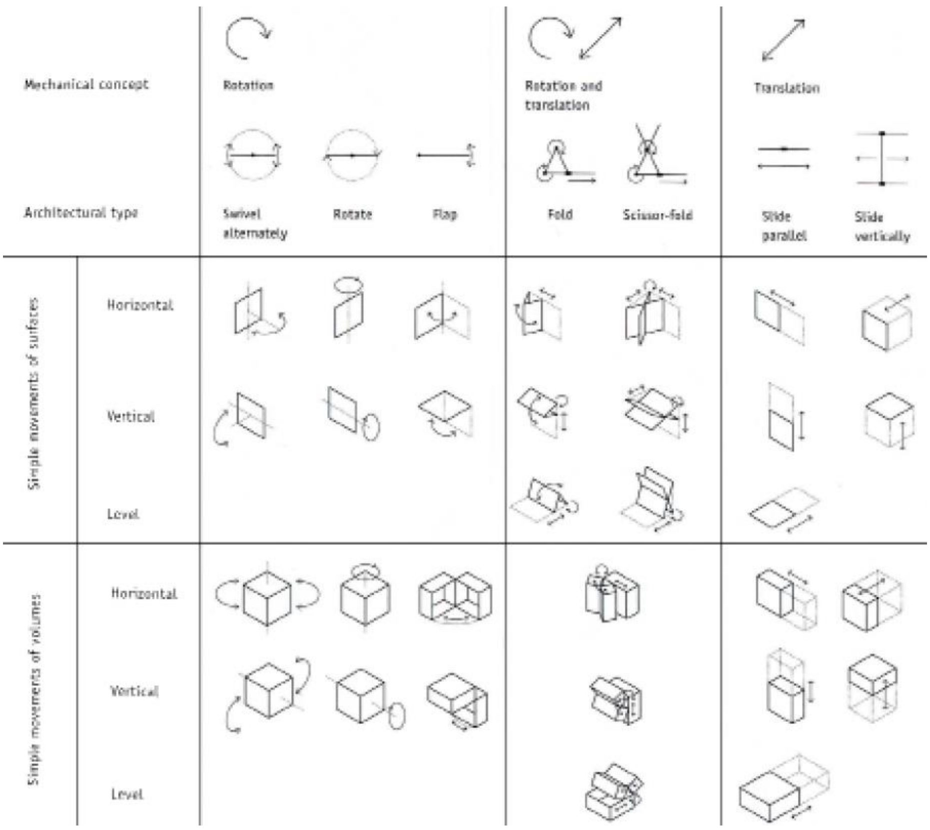
Figure 2.51. The Directions of Motion, (a) Three DOF for Rotation, (b) Three DOF for Translation (Werner, 2013)

The sizes of the preferred materials, their properties, and how they are combined are very important in determining the type of kinetic motion. Therefore, Elkhayat (2014) examined the kinetic system's architectural elements in five categories to determine the types of movement that a building can have. These are rigid, deformable, soft and flexible, elastic elements, and pneumatic forms.

i. The Movement of Rigid Elements

From Kugel's drawings dated 1979, it can be understood that rigid elements can have three basic movement types (Werner, 2013; Elkhayat, 2014). These are translation, rotation, and both translation and rotation, depending on the direction of movement (Table 2.7). The number of DOF varies according to the number of connection elements used in the mechanism and their properties (Tsai, 1999). In rigid kinetics structures, the hinge used for rotation and the rail used for slide provide mostly one degree of freedom to the structure. Elkhayat (2014) claimed that structures designed with rigid elements are the majority in architecture.

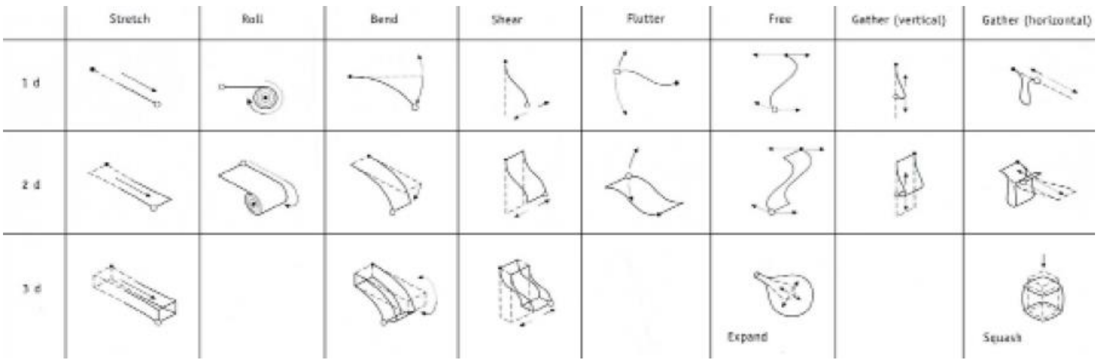
Table 2.7 Types of Movement of Rigid Architectural Elements based on Kugel's Drawings (Werner, 2013; Elkhayat, 2014)



ii. The Movement of Deformable Elements

Thanks to the use of deformable elements in architectural structures, the factors that restrict DOF can be reduced. Kugel's drawings referred to in the researches of Werner (2013) and Elkhayat (2014) are an indication of this (Table 2.8). If the sizes, weights, and material types of the elements in the mechanism allow deformation and transformation, stretch, roll, and bend movement types may exist in addition to the basic rotation and slide movements. According to Elkhayat (2014), spatial transformations cannot be achieved by grouping rigid architectural elements differently. Instead, they can be achieved in line with the motion capabilities of the elements and materials used. Therefore, deformable elements provide more mobility and adaptability to an architectural structure compared to rigid elements.

Table 2.8 Types of Movement of Deformable Architectural Elements based on Kugel's Drawings (Werner, 2013; Elkhayat, 2014)



iii. The Movement of Soft and Flexible Elements

Soft and flexible materials such as textile, rope, fiber, and woven fabric are mostly preferred in adaptive structures, as their shapes can easily change if an external force is applied (Elkhayat, 2014). They are lightweight and occupy a small space. Kronenburg (2007) emphasized that textiles and membranes are especially suitable for spatial divisions and hanging, gathering, and rolling systems. He also added that they require very little energy in their operations. However, when the force applied to soft and flexible elements is removed, they generally cannot regain their initial forms.

iv. The Movement of Elastic Elements

Unlike soft and flexible elements, elastic elements can regain their initial form after the removal of the external force. Therefore, they have more potential than the types mentioned earlier. However, according to Schumacher (2010), these elements' disadvantage is that they cannot be easily manufactured in the desired visual quality, size, and strength for large-scale uses. Therefore, elastic materials are mostly used in small-scale objects, such as steel springs and rubber dampers (Schumacher, 2010). When the advantages of elasticity are considered, it can be said that their greater presence in the design field will open new doors to kinetic architecture.

v. The Movement of Pneumatic Forms

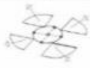
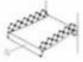
According to Werner (2013), pneumatic forms are deformable membranes having expandable movement type. However, according to Elkhayat (2014), these forms have a movement type that changes between inflated and deflated states. When inflated by pressure, they can acquire spatial form. When deflated, they occupy a very small volume. They can be constructed and deconstructed temporarily according to the architectural function.

2.3.4.2 Construction Systems

Construction systems of a kinetic structure can be determined in accordance with the desired type of movement in the building. Table 2.9 shows Kugel's drawings dated 1979 that classify the kinetic roofs' construction systems (Werner, 2013; Megahed, 2016). This classification depends on the direction and the type of movement, and it also sets an example for other building components. From these drawings, what kind of movement occurs in a moving or stationary load-bearing system and how flexible materials such as membranes affect this can be understood. For example, rigid construction systems are limited only with the movements of slide, fold and rotate.

It means that rigid elements in kinetic architecture may limit the design diversity and the adaptation ability of the structures to changing conditions.

Table 2.9 Comparative Chart between Type of Movement and Construction System based on Kugel's Drawings (Werner, 2013; Megahed, 2016)

		Geometric transitions in space			
		Movement direction			
Construction system	Movement type	Parallel	Central	Circular	Peripheral
Rigid constructions (rigid panels or structural segments)	Slide				
	Fold				
	Rotate				
Membranes, with stationary supporting structure	Gather or bunch				
	Roll		–		
Membranes, with movable supporting structure	Slide		–		–
	Fold				–
	Rotate	–	–		–

CHAPTER 3

MATERIAL AND METHOD

In order to understand how movement can be turned into an architectural space, the materials and methodologies of previous researches on the relevant topics were investigated. In light of the critical analysis made, the methodology of this research was formulated.

3.1 Material

The material of this thesis work consists of human motion data retrieved from the Carnegie Mellon University Graphics Lab (CMU-GL) Motion Capture Database (mocap.cs.cmu.edu) and computer software programs 3Ds Max, Maya with the scripting language Python and Rhinoceros with the plugins Grasshopper and Kangaroo Physics.

3.1.1 CMU-GL MoCap Database

The CMU-GL MoCap Database contains free motions captured through optical marker-based motion capture systems. The cameras, which surrounded a rectangular area of approximately 3m x 8m, were used to capture 41 markers on a black jumpsuit worn by different subjects (Figure 3.1). The obtained 3D human-motion data were transferred to digital platforms, simulated and edited there, and made available to the public. The interface of the database can be seen in Figure 3.2. The subjects whose data were collected and each of the capture attempts per subject were named with numbers. For this reason, motion codes were presented as subject-trial pairs in the database.

Figure 3.1. The Jumpsuit Used by CMU-GL, Having 41 Markers Taped on (Retrieved from mocap.cs.cmu.edu)

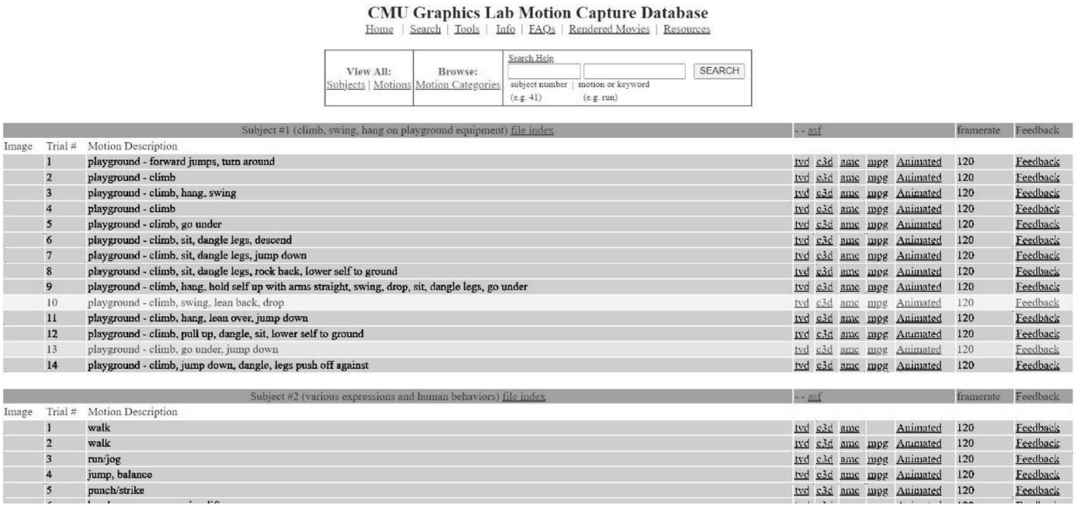


Figure 3.2. The Interface of the CMU Graphics Lab Motion Capture Database available at mocap.cs.cmu.edu

Within the scope of this study, 2605 human motions in this database were reviewed, and scenarios in which the motion trails of the markers have minimal overlaps with each other were selected by trial and error. Thus, the obtained 103 human motions formed the material of this study.

These selected motions were then classified into three categories: human interaction and communication, walking styles (embodying different emotions), and various expressions and human behaviors, having 26, 43, and 34 motion types, respectively. In order to animate these motion data as 3D Biped models, the 3ds Max friendly BVH file format release of the database was obtained from cgspeed.com. More information about motion categories is given under subheadings.

i. Category 1: Human Interaction and Communication

There are scenarios in the CMU Database in which the movements of two people were recorded simultaneously in the same physical environment. For instance, in the 'high-five, walk' motion scenario, subjects C and D are walking towards each other and performing a high-five. However, the movement data of these two people have been transferred to the digital environment as separate files and therefore are included in the database separately. In order to observe what kind of forms can arise from the interaction of two people, these separate files were brought together in the digital environment as part of this thesis. Therefore, 26 human motions in this category were grouped in pairs and reduced to 13 scenarios (Table 3.1). This is not the case with the motion data in the other two categories, which only contain one-subject motions.

Table 3.1 Category 1: Human Interaction and Communication (2-Subject Motions)

Original CMU Motion Code		Subject Code	Motion Description
Subject No	Trial No		
18 19	1	A B	A and B walk, shake hands
18 19	4	A B	A pulls B; B resists
18 19	9	A B	A and B communicate with each other with hand gestures, walk
20 21	2	C D	C and D link arms, walk
20 21	5	C D	C and D perform synchronized walk
20 21	7	C D	C and D perform soldiers march
20 21	11	C D	C and D perform high-five, walk
20 21	12	C D	C and D perform low-five, walk
20 21	13	C D	C and D play blind man's bluff (blindfold tag)
22 23	8	E F	E and F hold hands, swing arms, walk
22 23	16	E F	E and F perform synchronized jumping jacks
22 23	23	E F	E and F walk; E catches keys thrown by F
22 23	25	E F	E and F walk; E catches wallet thrown by F

ii. Category 2: Walking Styles (Embodying Different Emotions)

Some movement types have been performed too many times in the CMU Database. In particular, there is a large amount of data related to walking. The way people walk reflects their emotional state. Therefore, this category was created in order to observe what kinds of forms can arise from different emotions, walking habits, and interpretations (Table 3.2). A total of 43 human motions are available in this category.

Table 3.2 Category 2: Walking Styles (Embodying Different Emotions) (1-Subject)

CMU Motion Code		Motion Description
Subject No	Trial No	
36	1	walk on uneven terrain
82	9	confident walk forward
83	35	walk forward and step upstairs
90	32	moonwalk
91	10	slow walk
91	12	too cool walk
91	13	sad walk
91	14	depressed walk
91	17	quick walk
91	18	careful walk looking around
91	19	marching
91	20	shy walk
91	22	casual quick walk
91	32	scared walk
91	33	macho walk
91	34	normal walk
132	1	walk with arms out, balancing
132	16	walk crossover
132	37	marching
132	43	walk swinging shoulders
132	53	walk with legs apart
132	54	walk with wild arms
132	55	walk with wild legs
132	56	walk with wild legs without swinging arms
135	4	martial arts walks (front kick)
135	5	martial arts walks (gedanbarai)
135	7	martial arts walks (mawashigeri)
135	9	martial arts walks (oiduki)
135	10	martial arts walks (syutouuke)
138	16	walking while talking
142	4	cool walk
142	5	depressed walk
142	9	joy walk
142	10	lavish walk
142	11	marching
142	13	relaxed walk
142	14	rushed walk
142	15	sad walk
142	17	scared walk
142	19	shy walk
142	21	singing in the rain jump
142	22	sneaky walk
143	15	walk and step over

Among these data, some motion types were specifically selected and shown in Table 3.3 to examine further whether the same or similar scenarios performed by different subjects or interpreted differently by the same subject create variation in the generation of forms.

Table 3.3 Same or Similar Types of Movements Performed by Different Subjects

Original CMU Motion Code		Subject Code	Motion Description
Subject No	Trial No		
91	12	G	too cool walk
142	4	H	cool walk
91	13	G	sad walk
142	15	H	sad walk
91	14	G	depressed walk
142	5	H	depressed walk
91	20	G	shy walk
142	19	H	shy walk
91	17	G	quick walk
91	22	G	casual quick walk
142	14	H	rushed walk
91	32	G	scared walk
142	17	H	scared walk
91	19	G	marching
132	37	I	marching
142	11	H	marching

iii. Category 3: Various Expressions and Human Behaviors

This category was created by bringing together a mix of human motion scenarios, mostly having sudden changes. For instance, there are recordings such as switching to running while walking slowly or starting to jump while running. The aim was to observe how these sudden speed changes would be reflected on the forms. A total of 34 human motions are available in this category (Table 3.4).

Table 3.4 Category 3: Various Expressions and Human Behaviors (1 Subject)

CMU Motion Code		Motion Description
Subject No	Trial No	
2	3	run/jog
16	55	run
16	57	run/jog, sudden stop
43	3	playground - grip bar, swing body
49	4	run, leap
49	5	run, leap
74	14	slope 1
75	2	run jump
75	4	wide leg run
75	5	cross leg run
75	11	2 jump
75	13	hopscotch
81	13	jump backwards off ledge
86	7	walking, swinging arms, stretching
87	4	backflip
88	2	backflips, jump onto platform
90	15	front hand flip
90	29	sequence
104	8	start jog
104	55	start run
104	57	run stop
127	4	walk to run
127	13	run side step left
127	18	run stop run
127	19	run quick stop run
127	22	run jump stop run
127	25	run jump over
127	36	run over
127	38	run duck underneath
141	22	high five
143	2	run to stop
143	3	start to run
143	5	jumping distances
143	31	hopscotch

Among these data, the "run, leap" movement scenario was reinterpreted by the same person differently; hence it will be particularly examined to see whether their forms differ.

3.1.2 Computer Software

The software used in this study are 3Ds Max, Maya, and Rhinoceros. More information about them is given below.

i. 3Ds Max

3Ds Max is a modeling, animation, visualization, and rendering software. In this study, it was used only for converting the BVH file format release of CMU's MoCap database into 3D Biped format to use in Maya, as Maya does not support BHV file format.

ii. Maya

Maya is a software for modeling 3D objects and scenes, creating animation characters, and simulation. In this study, it was used to simulate motion trails and to create forms using these trails. In addition, it was utilized from Python scripting language in Maya to transform the motion trails into curves that can be used in form creation.

iii. Rhinoceros

Rhinoceros is a modeling, rendering, analysis, and fabrication software. Together with its parametric visual scripting interface Grasshopper, it was used for creating a kinetic model and simulating its movement mechanism in this study. Kangaroo Physics, which is a plugin for Grasshopper, was also utilized in the simulation process.

3.2 Method

The method of this research consists of seven steps, as seen in Figure 3.3. While the first five steps (Phase 1) were applied to all motion types selected as the research material, the last two steps (Phase 2) were continued for only one motion type. The outputs of the first five steps show the variety of forms that motion data can create.

The final output of the seven steps is a deployable personal space that is digitally designed, and its movement mechanism is simulated.

All these steps are explained in detail under the sections form finding phase and deployable personal space design phase through a selected human motion data that is ‘high-five, walk’ from the human interaction and communication category. The reason of preferring this category is that it consists of motion scenarios representing the interaction between two individuals, and therefore the deployable form-finding process of any scenario from this category is found to be more explorative and challenging. In addition, the motion type ‘high-five, walk’ was selected because it got the author's attention as being a frankly gesture.

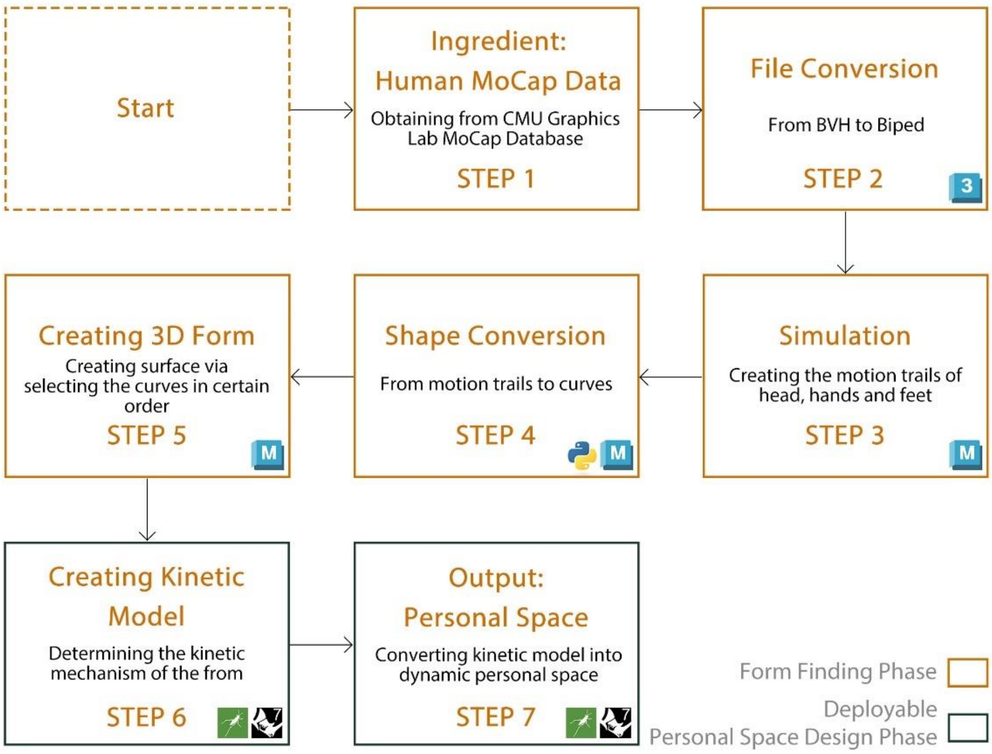


Figure 3.3. The Process of Using Human Motion Data as a Design Ingredient and Transforming it Into a Deployable Personal Space

3.2.1 Form Finding Phase: Steps 1 to 5

i. Step 1: Obtaining human motion data

As in most studies reported in the literature, obtaining these data with the Optical MoCap System was desired, as it provides more precise information. However, instead of capturing motion personally, the online motion capture database of CMU Graphics Lab containing already captured and edited motion data using the Optical MoCap System was used. In the Optical MoCap System, by using sensors positioned on certain joints of the human body, the displacements of each sensor (motion trails) during the performance can be tracked and simulated in the digital environment. For instance, the capture of the motion 'high-five, walk' with the Optical MoCap System is shown in Figure 3.4. The focus of this work was to obtain various forms by using these human motion trails as a design ingredient to eventually create a deployable personal space.

Figure 3.4. Screenshots Taken From the MPG File of the Motion Type ‘High-Five, Walk’ (CMU Motion Code: 20-21,11) Showing the Motion Capture Environment. This Motion Type Exists in Category 1 in This Work.

What kind of motions would be retrieved from the CMU MoCap database depended on an experimental study. In order to avoid problems that might complicate the use of space in the deployable form to be achieved and limit the movement ability of the structure, the trails of the human joints should have minimal overlaps. However, it should be noted that dealing with human body motion is very complex, and the vast majority of captured motions have overlapping trails, as seen in Figure 3.5. In order to minimize this complexity, it was decided to use the motion trails of only five joints of the human body in this study, which are the head, hands, and feet (Figure 3.6). Accordingly, all motion scenarios in the database were reviewed, and the ones in which the motion trails of the five joints had none or few intersections with each other were selected by trial and error. In addition, when necessary, the frame range with less overlaps was preferred instead of the entire movement range.

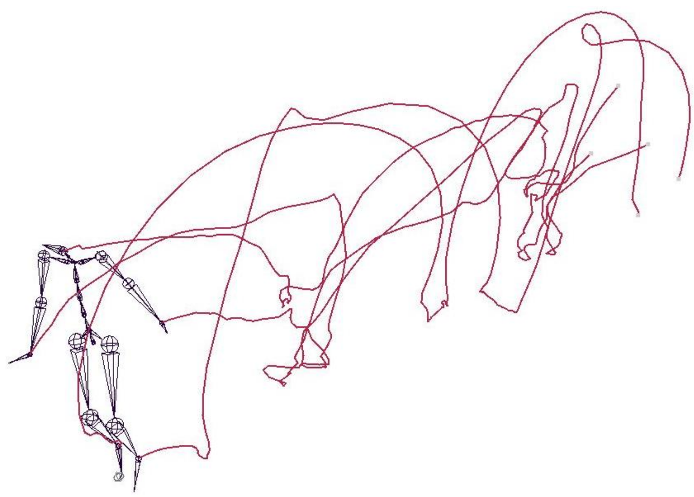


Figure 3.5. Intersecting Motion Trails of a Person Doing Cartwheels (CMU Motion Code: 49-8). Could not be Included in the Material of this Research

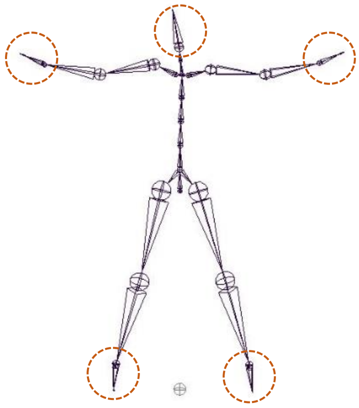


Figure 3.6. The Body Parts Used in the Process of Form Generation: Head, Hands, and Feet

After this selection process, all collected motions were grouped into three categories. These are human interaction and communication, walking styles (embodying different emotions), and various expressions and human behaviors (details can be seen in Section 3.1.1). It is desired to observe the changing patterns created by different motion types within each category and to show the diversity of forms.

ii. Step 2: Converting file format

The BVH file format release of CMU’s motion capture database for selected motion types was obtained from cgspeed.com and converted to 3D human skeletal models, namely Biped format in 3ds Max. Then they were transferred to the Maya program. This step was applied simultaneously for the ‘high-five, walk’ motion of two people in separate files in the database (Figure 3.7.a). Thus, the biped models of two people were transferred to the Maya program as a single file (Figure 3.7.b).

(a)

(b)

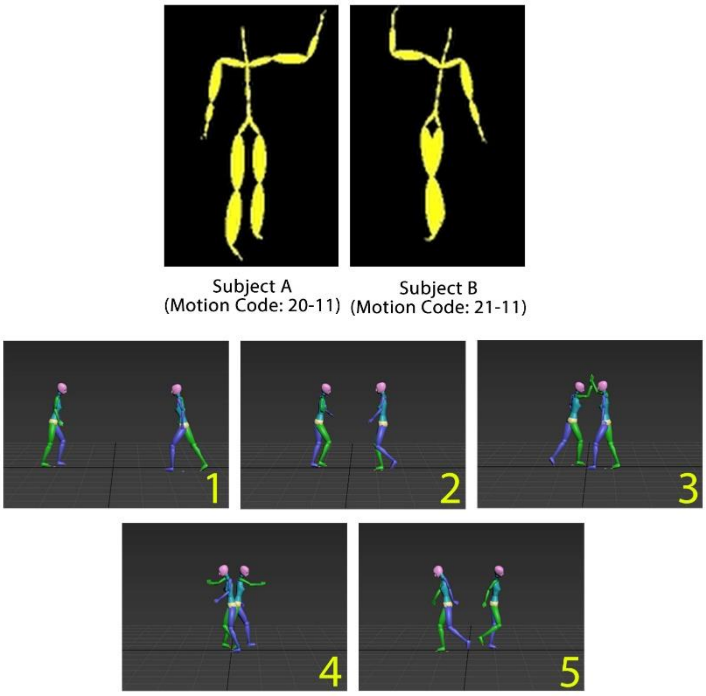


Figure 3.7. (a) Screenshots Taken From the ‘High-Five, Walk’ Animations of Subjects A and B, (b) Combined Biped Models of Both Subjects in 3ds Max

iii. Step 3: Creating motion trails

In the third step, the invisible traces of the head, hands, and feet during movement were simulated with the ‘Create Editable Motion Trail’ command (Figure 3.8) in the Maya program. Frame intervals that appear to have excessive overlaps were excluded. However, the obtained motion trails could not be used to create surfaces.

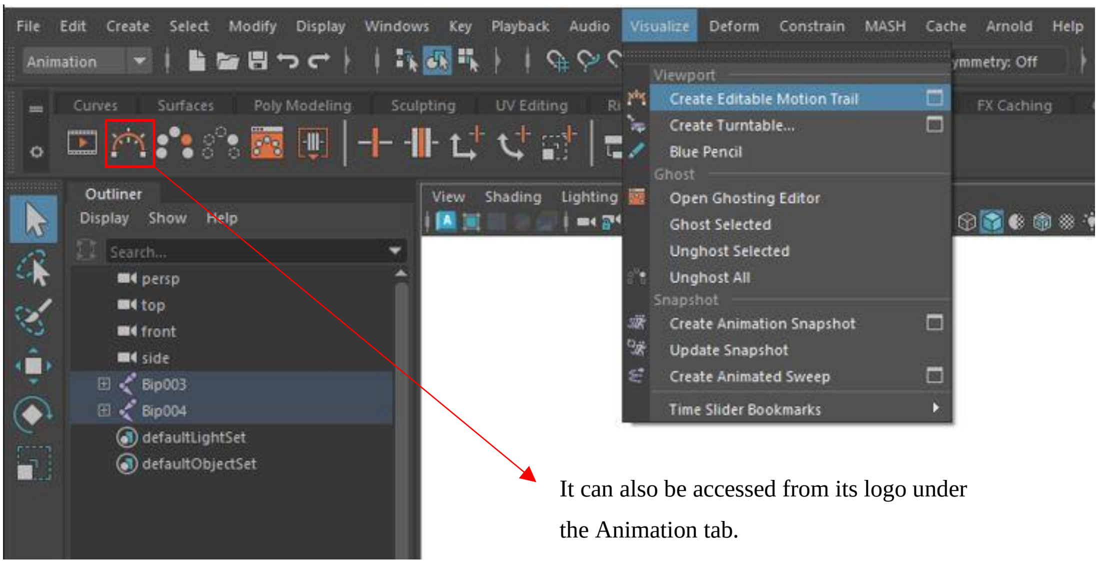


Figure 3.8. Motion Trail Command in Maya

iv. Step 4: Converting motion trails into curves

As the next step, motion trails were converted into curves so that they could be used to create surfaces; this was achieved with the code seen in Figure 3.9, which was written using the Python coding language in Maya by following the steps in the tutorials of Athias (2020). In order to provide clearance in the targetted form, some curves were relocated or excluded.

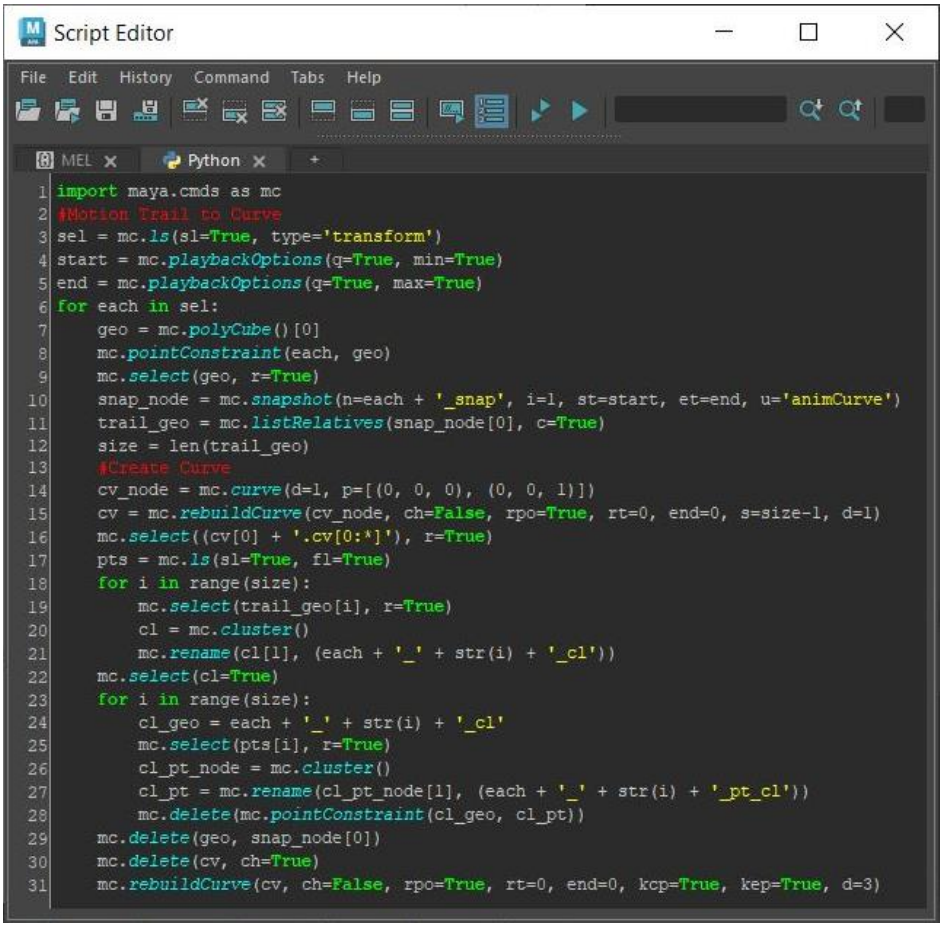


Figure 3.9. The Code Writing interface of Maya, Showing the Python Code Written by Following the Steps in the Tutorials of Athias (2020) to Convert Motion Trails into Curves (Available in the Appendix of this Work)

v. Step 5: Converting curves to surfaces

In the fifth step, the curves were selected in a certain order, and a surface was created with Maya's 'Loft' command (Figure 3.10).

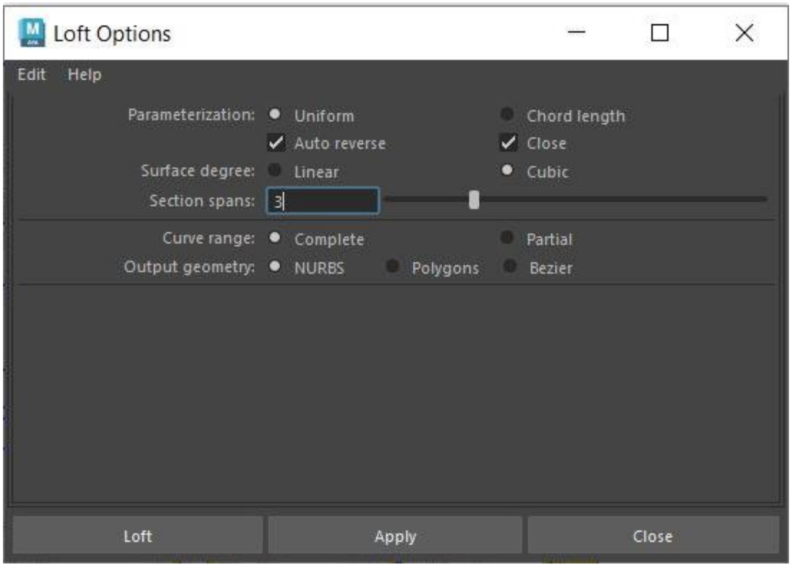


Figure 3.10. Loft Command in Maya - The Settings Used in the Creation of a Surface From Curves

The steps of Phase 1, which are explained through the 'high-five walk' motion scenario (Figure 3.11), were applied for a total of 103 motion scenarios one by one, and different forms were obtained. The results of this phase are discussed in detail in the Results and Discussion Section 4.1.

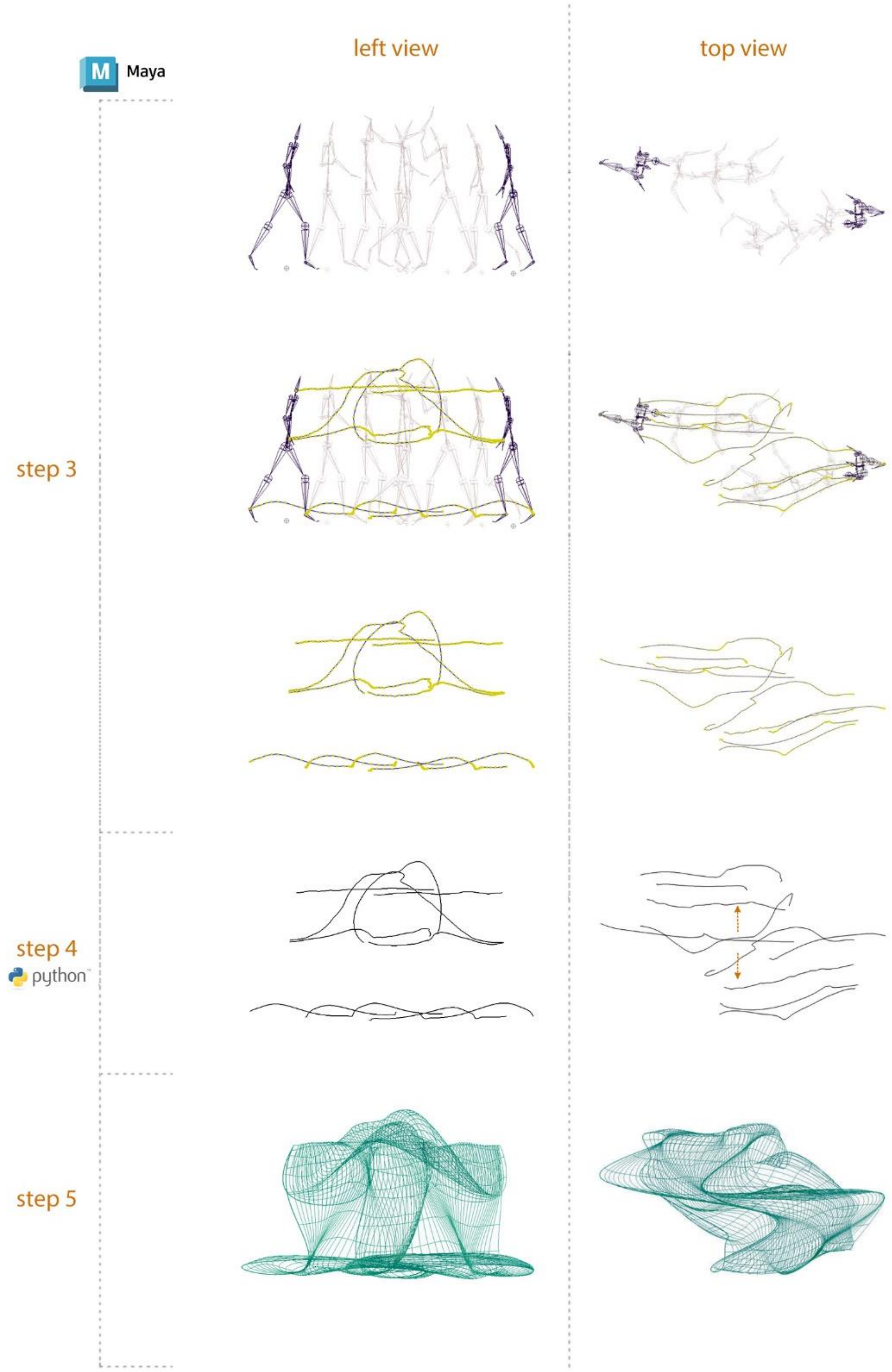


Figure 3.11. The Steps Applied in Maya for ‘High-Five, Walk’. Step 3: Visualizing the Traces of the Head, Hands, and Feet. Step 4: Converting the Motion Traces into Curves with Python Coding. Pushing out the Curves of the Hands and Feet to Provide Clearance Within the Targetted Form. Step 5: Creating a Surface Around the Curves

3.2.2 Deployable Personal Space Design Phase: Steps 6 & 7

vi. Step 6: Converting form into kinetic model

The resulting form of the motion ‘high-five, walk’ was transferred into the parametric modeling program Rhinoceros to apply the sixth step. In here, the kinetic mechanism of the form was determined with the help of the interface Grasshopper. The process is explained in detail in the following.

In order to obtain a deployable form, modular parts that form a whole when they come together are needed, and by giving mobility to these parts, it is ensured that the whole moves. Within the framework of this logic, it was planned to divide the form, which was transferred from Maya to the Rhinoceros program, into parts, and to make use of the isocurves on the undulating surface of the form to obtain translation movement on the y-axis. For this purpose, isocurve formations on the surface were investigated (Figure 3.12).

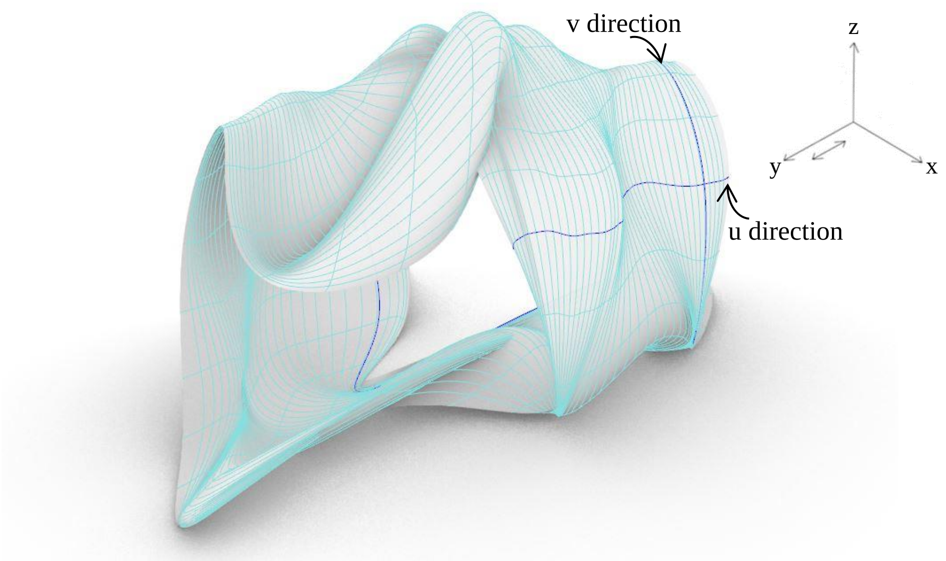


Figure 3.12. The Isocurves Formation on the Surface of the Form in the U and V Directions

The position and direction of movement at a certain moment is called the frame. The motion trails, which created the form, consist of a combination of the markers’ 3D positions in each frame during movement. Therefore, the vertically oriented isocurves on the surface correspond to the change of movement in each frame. The frame distribution is shaped according to the changes in the speed of the subject (human). If the movement is fast, the number of frames is low; hence, isocurve formation on the surface is wide apart. On the other hand, if the movement is slow, the number of frames is high; therefore, isocurve formation is dense. These changes caused the surface to take on a sinuous form. The areas with isocurves closely spaced to each other were selected with 'ExtractIsocurve' and 'DupBorder' commands of Rhinoceros.

Later on, curves at equal intervals were created between the selected curves with the Rhinoceros 'TweenCurves' command. Then, four new closed surfaces with smoother transitions were created in these areas with the 'Loft' command.

Afterward, the obtained four surfaces were introduced to the parametric modeling tool Grasshopper. The script in Figure 3.13 was applied separately for each surface to give thickness. As a result, four rigid cords were created. Different cord thicknesses can be given by changing the thickness value.

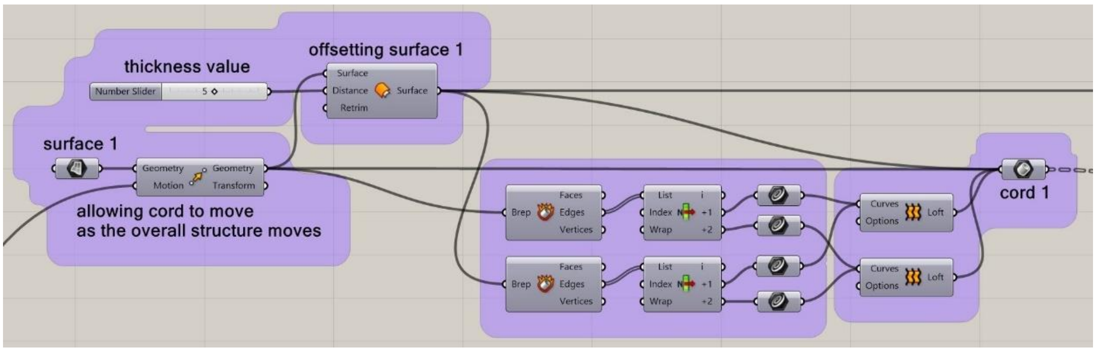


Figure 3.13. The Grasshopper Script Transforming the Surfaces Created in the Boundary Areas of the Form into Cords by Giving Thickness

It was envisaged that these rigid parts could be given one DOF translation movement parallel to the y-axis (previously shown in Figure 3.12). Accordingly, it was decided to use a membrane structural system consisting of a membrane in tension and supporting rigid elements. It was planned to create membranes using the surfaces between the rigid four cords and to give a tensile quality to adapt to the deformation arising from the back-and-forth movements of the rigid cords.

In this respect, Kangaroo Physics, a Grasshopper plugin, was needed to transform surfaces into tensile structures. This plugin has components that allow form-finding and physics simulation. The script in Figure 3.14 was applied separately for the three surfaces between the cords. Firstly, a mesh was obtained from the surface with the 'MeshSurface' command, then it was divided into points in the u and v directions, and the points located on the edges were obtained with the 'NakedVertices' command. With the 'ClosestPoint' command, these points were provided to catch the closest points on the cords' surfaces and were defined as the anchor points where the tensile membrane will be attached. A translation movement parallel to the y-axis was given to the tensile membrane.

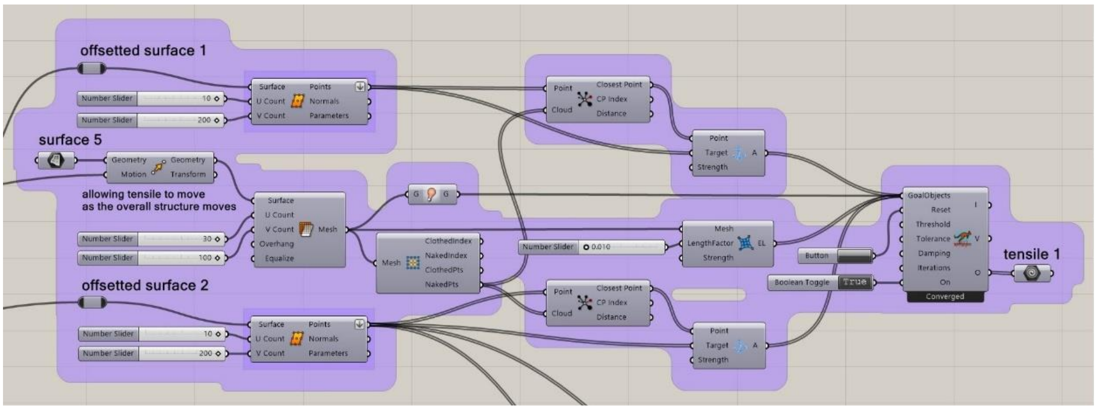


Figure 3.14. The Grasshopper Script Transforming the Surfaces Remaining Between the Cords of the Form into Tensile Membranes

In order to support the movement of the tensile membrane structure, a tubular exoskeletal structure was parametrically designed from which it was to be suspended. It encloses the entire form and adapts to its translation movement through its pantographic system. Its design process is explained in detail below.

The tubular structure consists of a combination of angulated and translational units (Figure 3.15). Angulated units form the main scissors system of the structure, while translational units connect to the pivots of the main scissors and fit in between as sub-scissors.

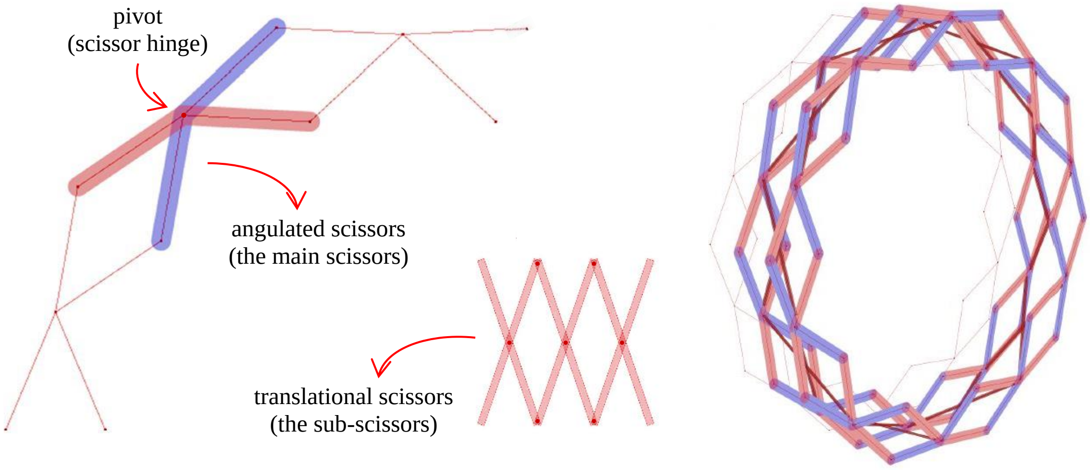


Figure 3.15. The Angulated and Translational Units of the Pantographic Tubular Structure and the Way They Connect

The design process of the tubular structure started with the parametric design of the main scissors system based on an ellipse shape in order to have spaces on the sides from where curving ramps can rise to access the suspended structure, on both ends of the tube. For this reason, firstly an ellipse was defined with the Grasshopper script in Figure 3.16, and this ellipse was converted to a polygon with 10 equal sides to have an angulated unit on each side. The obtained items were duplicated to create binary parts of the scissor unit.

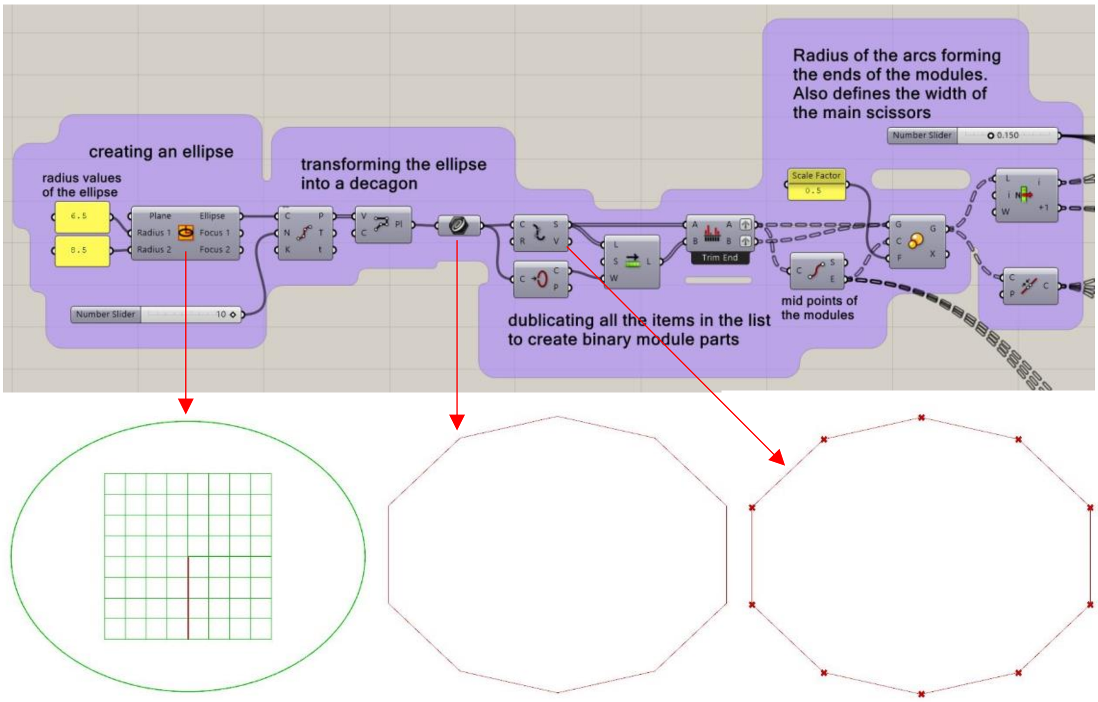


Figure 3.16. The Grasshopper Script and the Display of Creating an Ellipse, Turning it into a Decagon, and Duplicating all the Items to Create Binary Parts

Then, the width of the main scissor elements was determined by offsetting the 10-sided polygon (Figure 3.17). The ends of the bars forming the angulated unit were rounded. By changing the given parametric radius value, the width of the main scissors can be altered. Later on, surfaces were created between the offset curves.

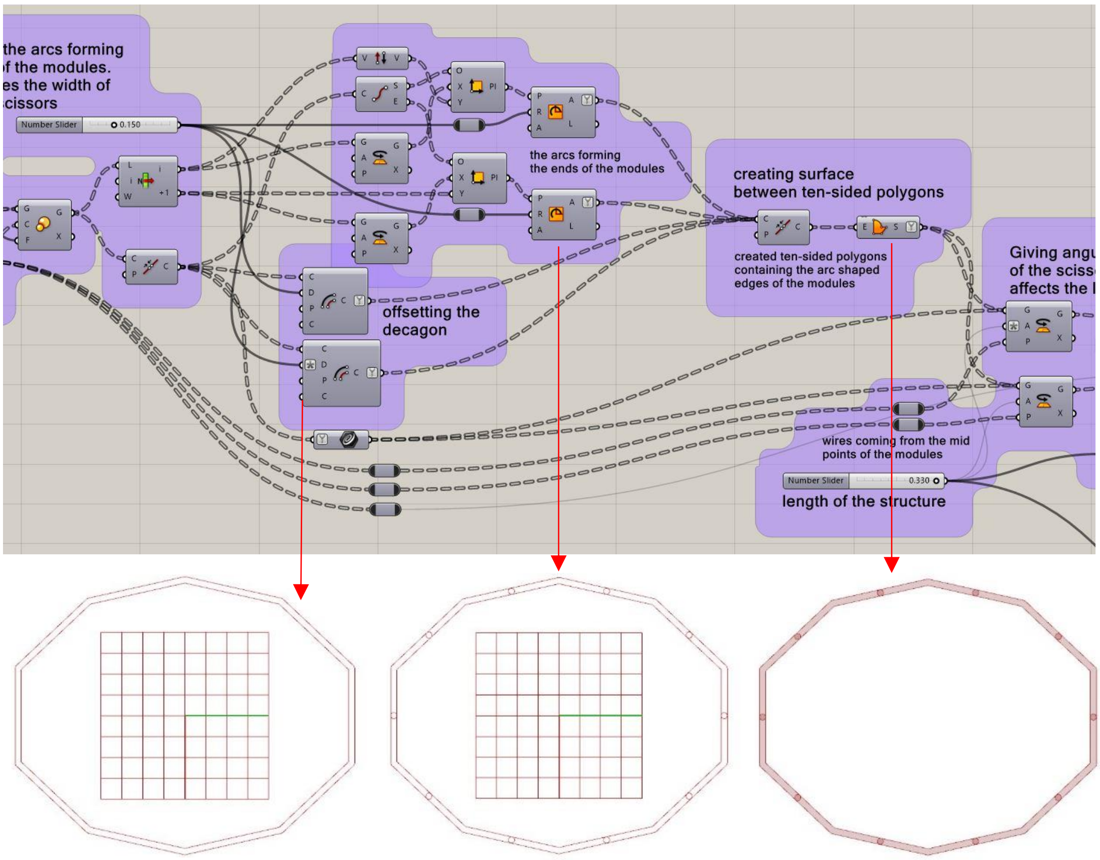


Figure 3.17. The Grasshopper Script and the Display of Offsetting the Decagon, Creating Arcs at the Ends of the Scissor Bars, and Creating a Surface Between the Polygons

Afterward, an angle was defined between the binary parts of the scissor unit (Figure 3.18). Changing the angle value affects the deployability of the mechanism. The separated scissor bars were demonstrated using the colors blue and red. They were then extruded, hence given a thickness.

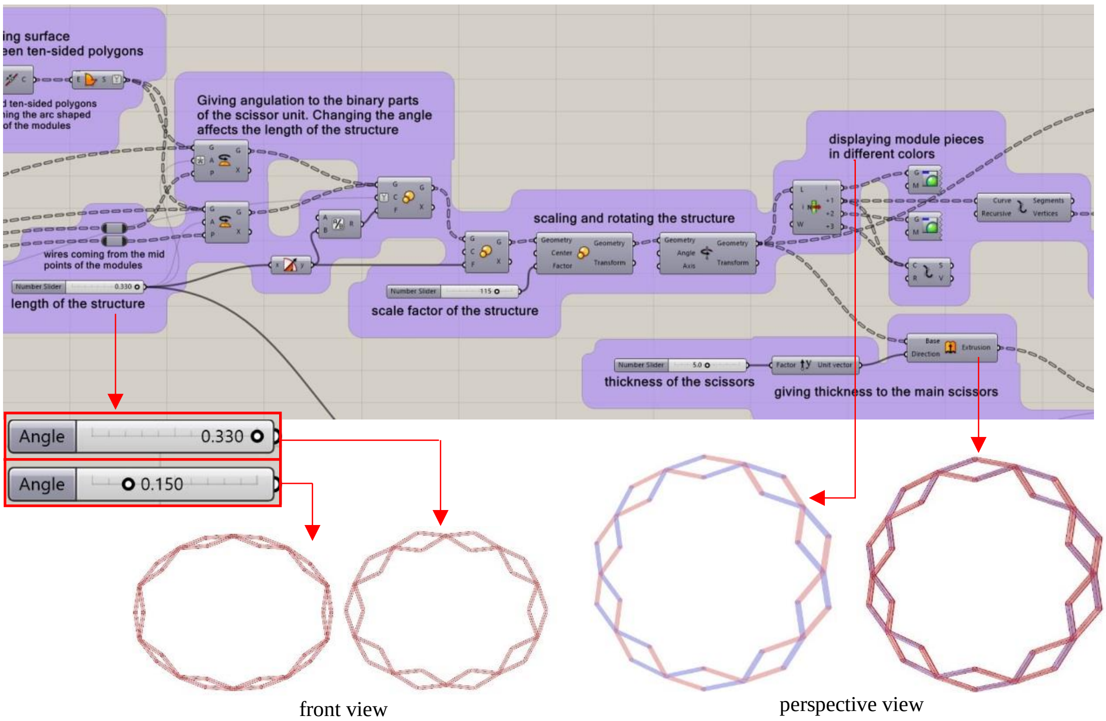


Figure 3.18. The Grasshopper Script and the Display of Defining the Deployment Angle Between the Binary Parts of the Scissor Unit, Demonstrating the Bars in Blue and Red Colors, and Giving Them a Thickness

The main scissors of the tubular structure were formed by creating an array of 10-sided polygons consisting of 10 angulated units on each edge (Figure 3.19). The array count and the deployment angle were determined considering the area occupied by the tensile membrane structure to be positioned inside.

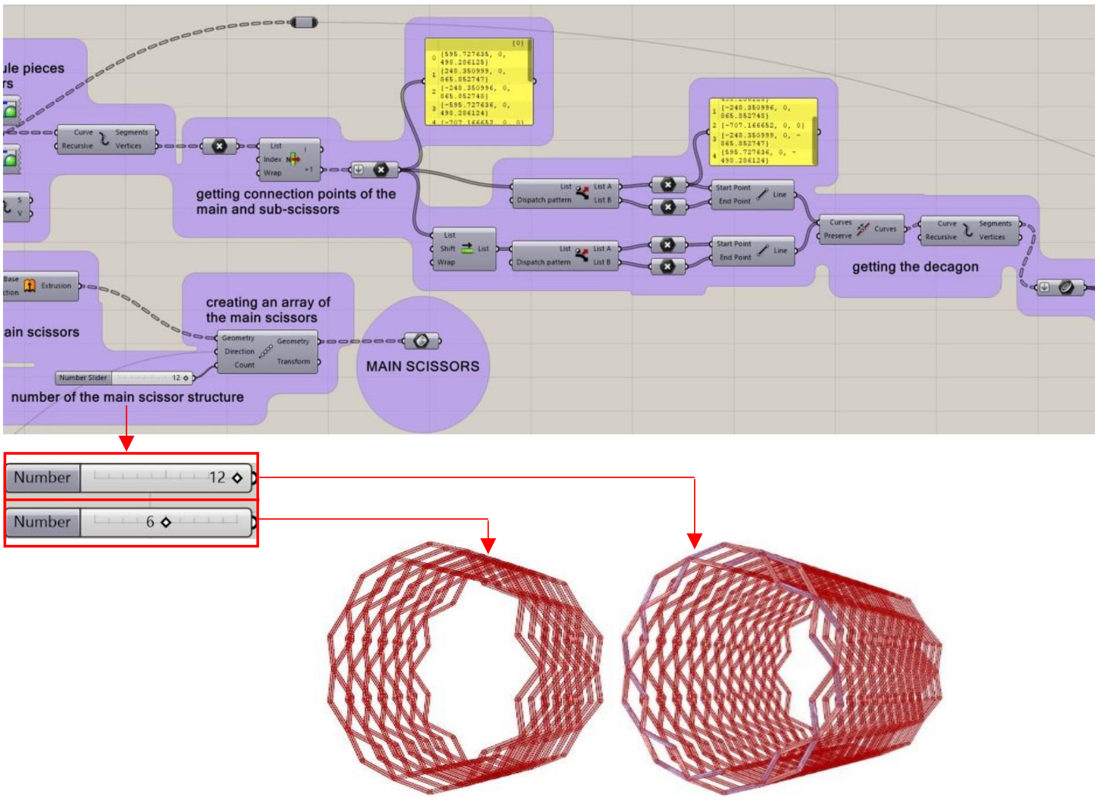


Figure 3.19. The Grasshopper Script and the Display of Creating an Array of 10-sided Polygons Consisting of 10 Angulated Units on Each Edge, and Extracting the Pivots of the Angulated Units on the Decagon

Regarding the design process of the sub-scissors, to place them in-between the main scissors lined up one after another, a line was created whose length is the distance between the pivot points of two angulated units (Figure 3.20). Then this line was rotated and arrayed. The number of lines is one less than the number of 10-sided polygons made up of angulated scissors as they will fit between the polygons. The distance between the lines is the length of the y-component of a vector whose starting point is the origin, located on the YZ plane, and has the same length as the created line (since the translation will be done on the y-axis). Then, all the lines were mirrored to obtain scissor units.

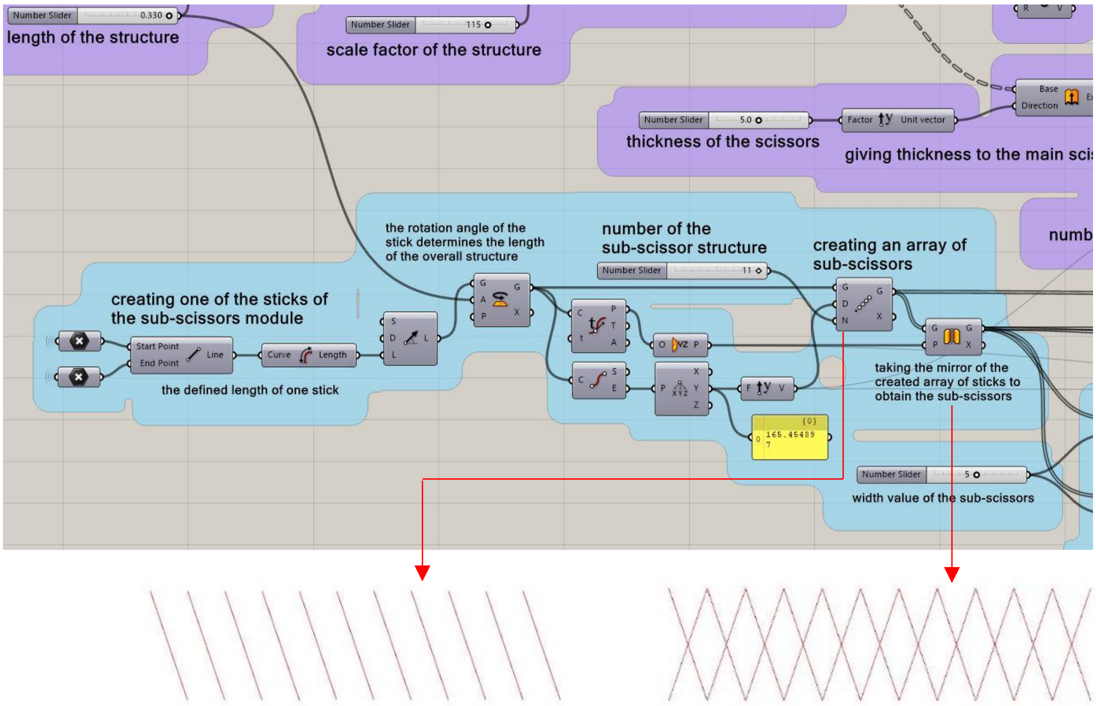


Figure 3.20. The Grasshopper Script and the Display of Creating, Rotating, Arraying and Mirroring a Line to Form Translational Scissors

Afterward, by taking the offsets of the lines, the scissors were given width, and surfaces were created between the offset lines (Figure 3.21). These operations were applied to the binary elements with the mirror command.

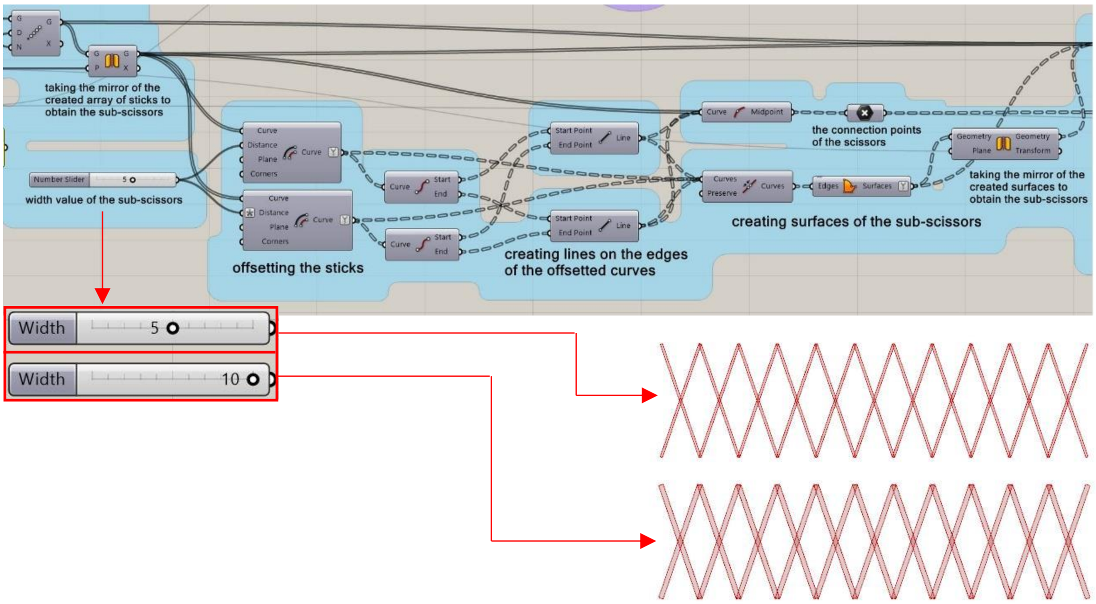


Figure 3.21. The Grasshopper Script and the Display of Taking Offsets of the Created Lines and Creating Surfaces In-Between

Then, the surfaces were extruded to give thickness to the sub-scissors and connected to the main scissors from the pivots to create the overall pantograph structure, as shown in Figures 3.22 and 3.23.

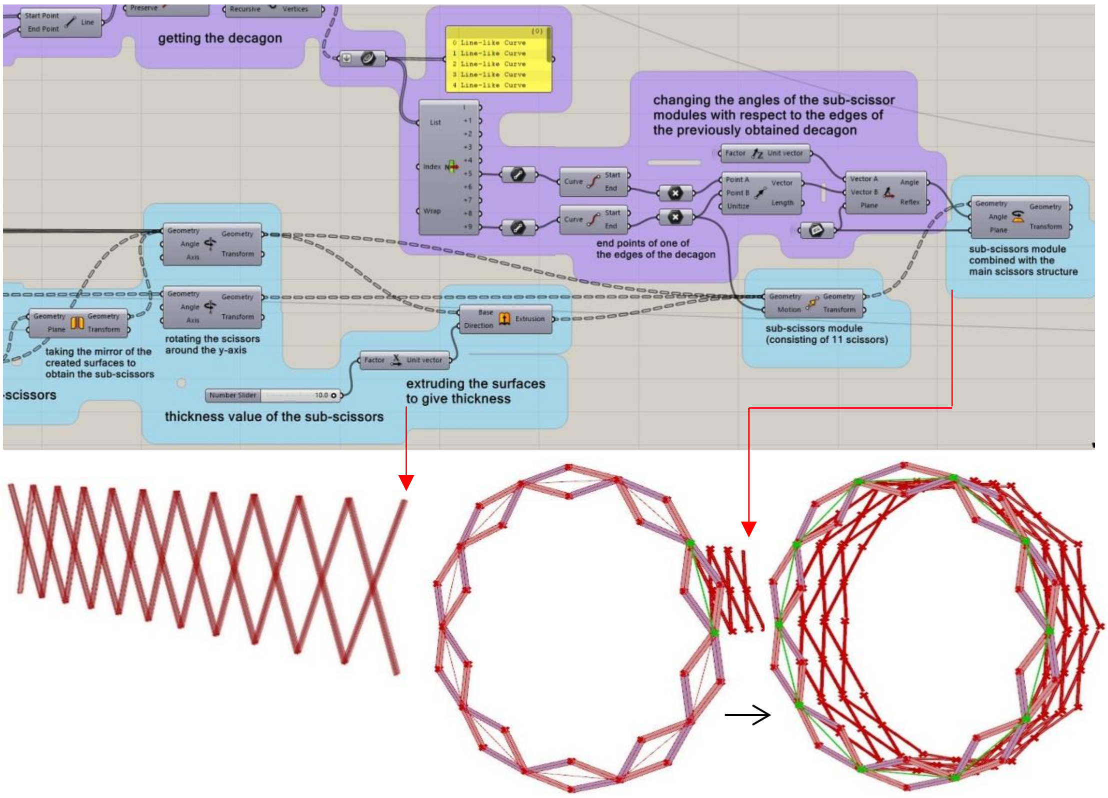


Figure 3.22. The Grasshopper Script and the Display of Extruding the Sub-Scissors and Connecting Them to the Pivots of the Main Scissors

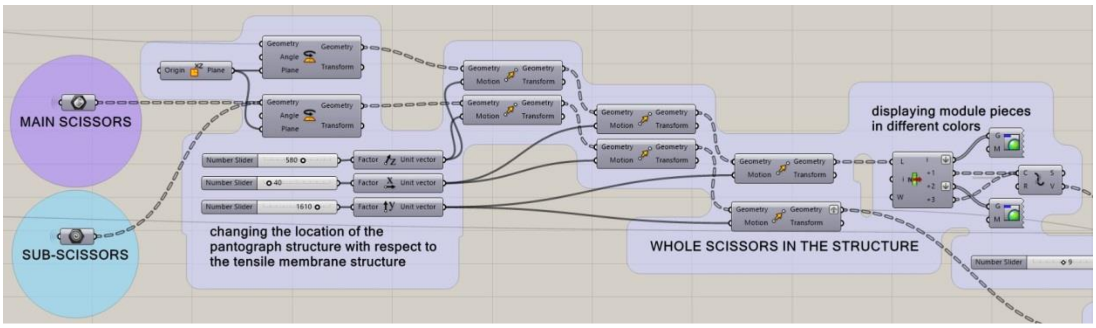


Figure 3.23. The Grasshopper Script of Connecting All Scissors to Create the Overall Pantograph Structure

Finally, the tubular system design was completed by adding joints to the junction points of all scissors (Figure 3.24).

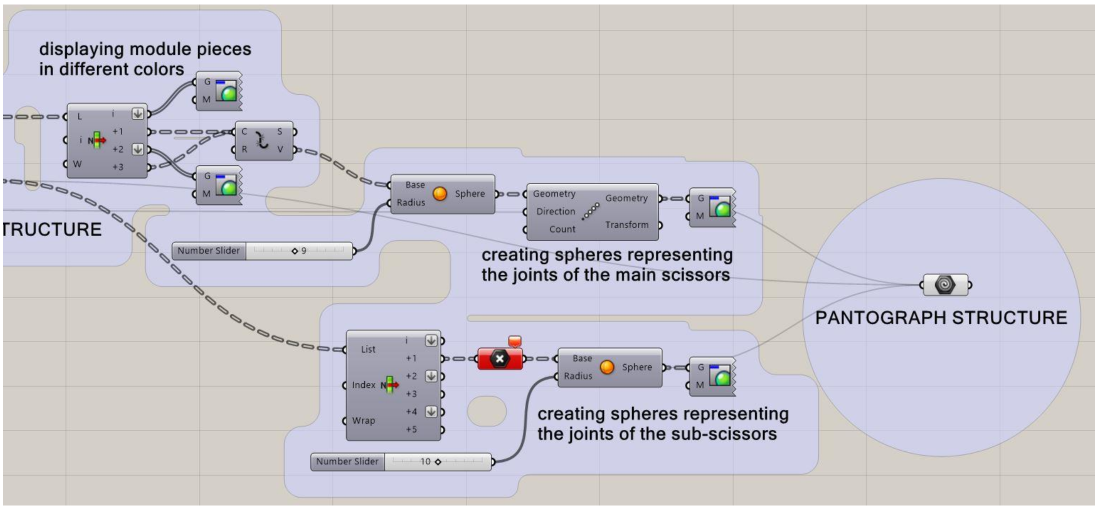


Figure 3.24. The Grasshopper Script of Adding Joints to the Junction Points of All Scissors

In order to hang the tensile membrane form inside this tubular design using cables, support points have been determined on the places where the cords of the form are bent, and these points were introduced to Grasshopper. Meantime, the support points to which the other ends of the cables will be connected were identified on the external tubular structure via the script in Figure 3.25. The included command 'ClosestPoint' allowed the support points on the cords to be connected to the nearest support points on the tubular system. Later on, the resulting cables were given thickness.

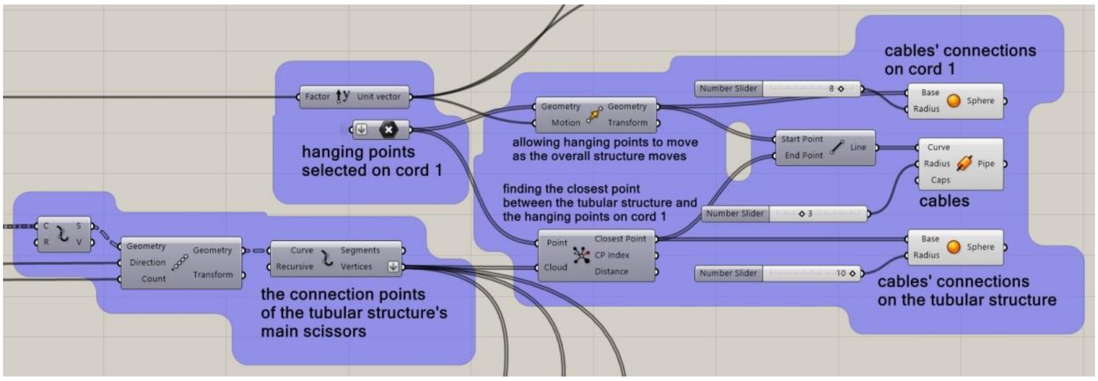


Figure 3.25. The Grasshopper Script Identifying the Support Points on the External Tubular Structure, Connecting Them to the Support Points on the Cords, and Creating the Cables

These cables do not interrupt the translation movement of the overall structure, and thanks to their flexible qualities, they can fulfill their task in all states of the structure within the defined deployment values.

vii. Step 7: Converting kinetic model into dynamic personal space

In the seventh step, the form was given a function as a pavilion in light of the information given in the literature on an architectural personal space. Foldable curving ramps rising from the sides were added to both ends of the tubular structure to allow access to the suspended form.

CHAPTER 4

RESULT AND DISCUSSION

This chapter firstly covers the outputs of the form finding experiment conducted with 103 human motions. Then discusses the diversity of forms in each motion category and how they can contribute to the architectural design process. Finally, the chapter outlines the results of the design phase of a deployable personal space created from one human motion selected among the material, that is, 'high-five, walk'.

4.1 Results of Phase 1: Form Finding

The method for the form finding experiment led to the creation of varying forms. It has been observed that this variation is affected by the shapes, positions, numbers, and selection orders of the curves obtained from the motion trails and generating the forms. These are discussed in detail in the sub-headings.

i. The shapes of curves

The shapes of the curves are formed according to the motion scenario and the person(s) performing it. In the CMU-GL MoCap Database, there are hundreds of motion scenarios from dance to sports, from everyday behaviors to interaction with the environment, and there are nearly 150 people who were recorded while performing them. There are recordings of the same type of motion being performed more than once by different people and even reinterpreted by them in different variations. It is believed by the author that this diversity of the database allows to obtain an unlimited number of forms since varying shapes of curves can be created from each motion; hence, it increases the creativity in the design process. Among all the motions available in the database, around a hundred of them were utilized in this study as per the determined design method. There is still the potential to get different results by developing different design methods and/or using different MoCap databases.

ii. The positions of curves

In the form finding process, the motion data for the head, hands, and feet, whose motion trails are formed far from each other, were preferred in this study. Utilizing more body joints or preferring the joints close to each other may cause unusable spaces in the form as it will result in motion curves that overlap or are too close and eventually offer less clearance when turned into form.

iii. The number of curves

Since only five joints were included in the scope of this study, the number of curves is a maximum of five for the motion types performed by a single person and a maximum of ten for the ones performed by two persons. In the case of two-person motions, the number of curves was reduced by excluding one of the body parts' motion when overlaps were observed.

iv. The selection orders of curves

In Maya, the program in which the form finding process was carried out, the 'loft' command can create a closed or open surface by following curves in a selected order. Accordingly, experiments were made by choosing the curves in different orders, and the created surfaces that got the author's attention more were included in the study.

Forms created in accordance with the above-mentioned form finding criteria are evaluated below for each movement category presented in section 3.1.1.

4.1.1 Forms Created from Two People's Interaction

The forms created by using human interaction and communication types of motions are shown in Table 4.1. The use of motion scenarios performed by two persons created more curve diversity as the number of motion data utilized increased. Accordingly, the variation in the selection order of the curves led to different form versions of the same motion type (e.g., two forms were created from the motion scenario 'walk, shake hands').

The motion curves of synchronized motions such as 'synchronized walk', and 'soldiers march' or motions that create indirect synchronization due to the body contact such as 'link arms, walk' and 'hold hands, swing arms, walk' created symmetrical undulations on the surfaces and allowed to obtain shapely forms.

Side-to-side performed motions, such as 'conversation, walk' or 'link arms, walk' enabled the motion curves to position side-to-side and thus allowed to obtain wide forms. On the other hand, face-to-face performed motions, such as 'walk, shake hands' or 'synchronized jumping jacks' have created narrow forms.

As seen in the 'blind man's bluff' motion type, asymmetrical undulations on the surfaces, and therefore, complex forms are obtained when the motion curves are intertwined.

Table 4.1 Forms Created from Two People's Interaction

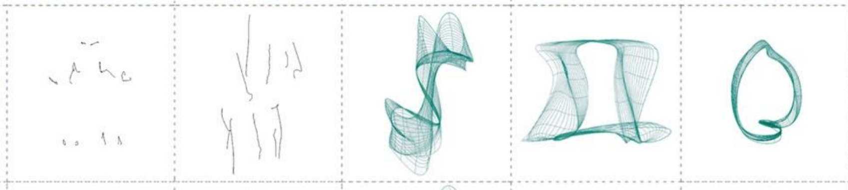
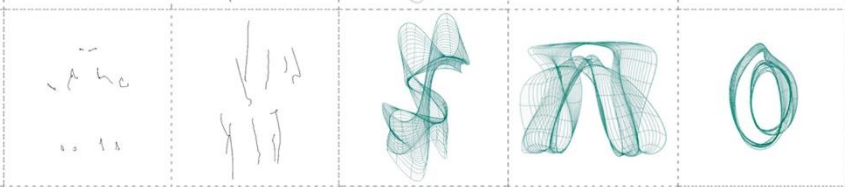
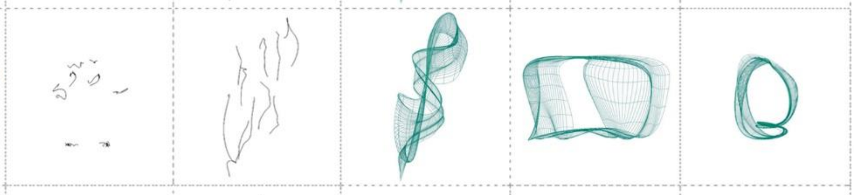
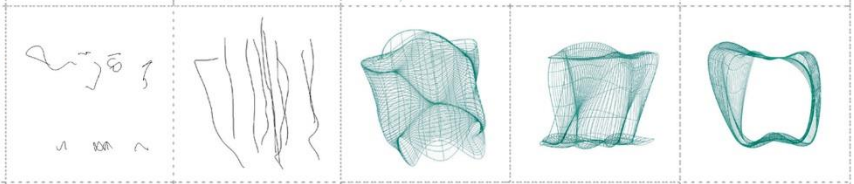
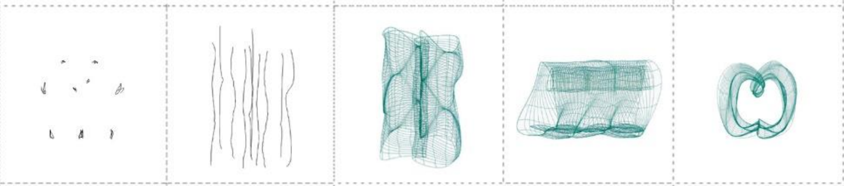
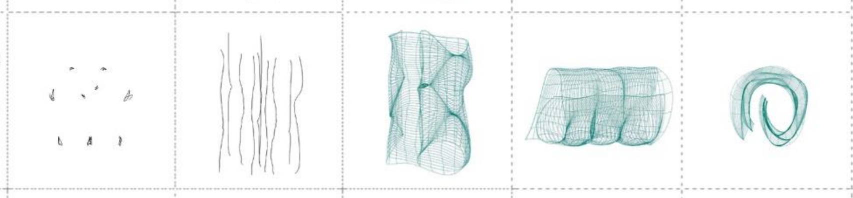
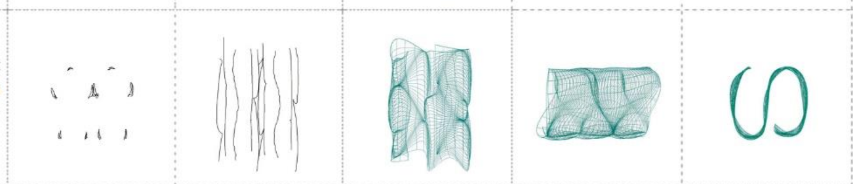
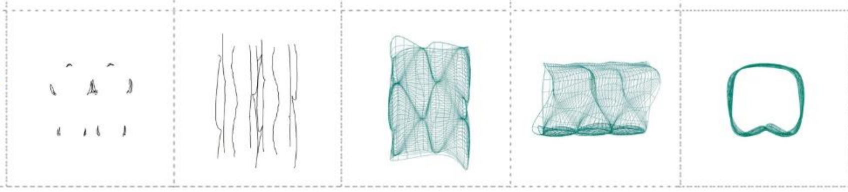
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: walk, shake hands CMU Motion Code: 18-1 & 19-1					
Motion Description: walk, shake hands CMU Motion Code: 18-1 & 19-1 (version 2)					
Motion Description: A pulls B; B resists CMU Motion Code: 18-4 & 19-4					
Motion Description: A pulls B; B resists CMU Motion Code: 18-4 & 19-4 (version 2)					
Motion Description: conversation - explain with hand gestures, walk CMU Motion Code: 18-9 & 19-9					
Motion Description: link arms, walk CMU Motion Code: 20-2 & 21-2					
Motion Description: link arms, walk CMU Motion Code: 20-2 & 21-2 (version 2)					
Motion Description: synchronized walk CMU Motion Code: 20-5 & 21-5					
Motion Description: synchronized walk CMU Motion Code: 20-5 & 21-5 (version 2)					

Table 4.1 (continued) Forms Created from Two People's Interaction

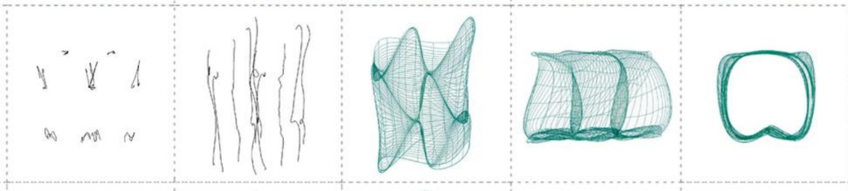
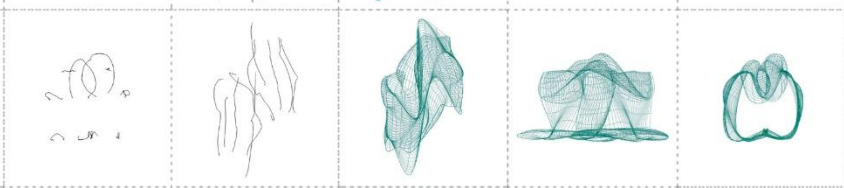
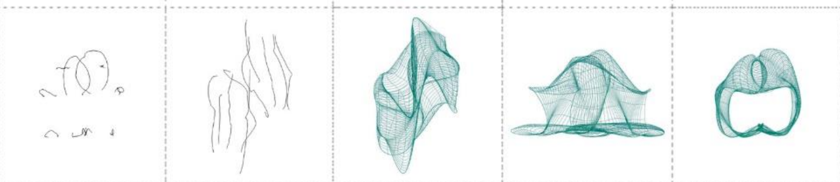
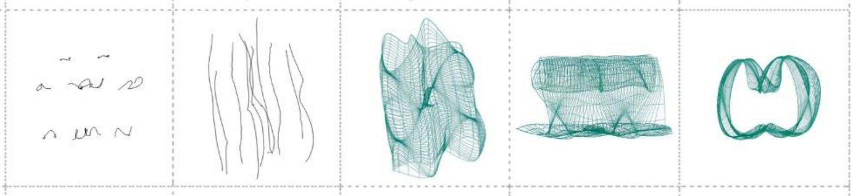
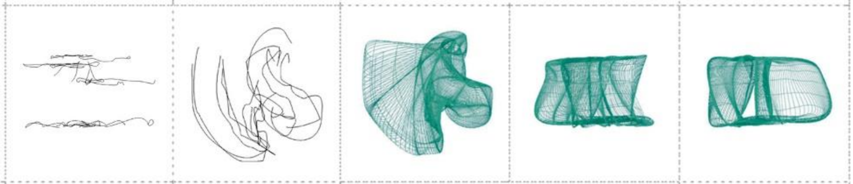
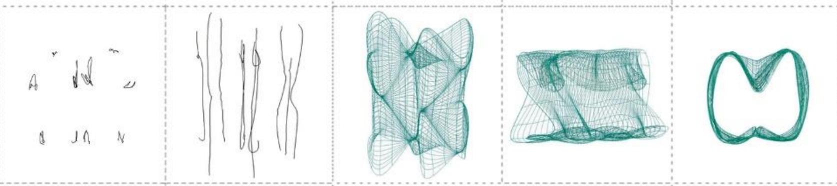
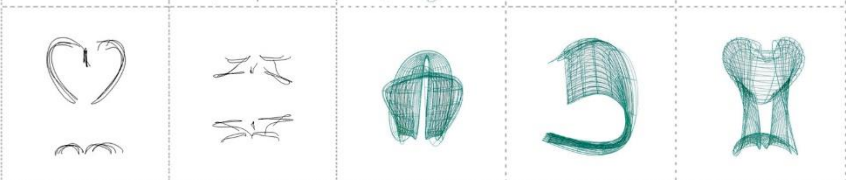
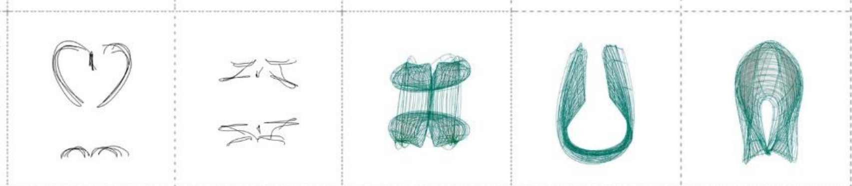
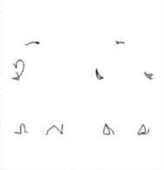
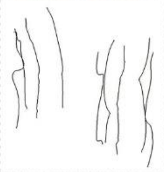
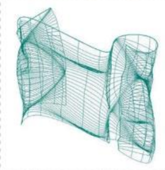
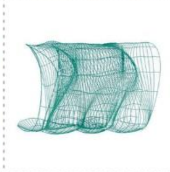
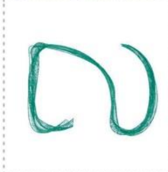
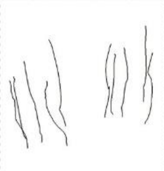
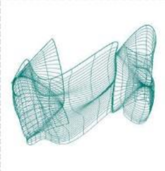
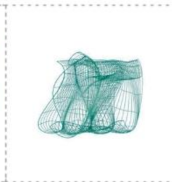
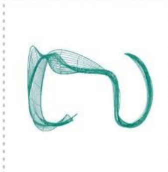
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: soldiers march CMU Motion Code: 20-7 & 21-7					
Motion Description: high-five, walk CMU Motion Code: 20-11 & 21-11					
Motion Description: high-five, walk CMU Motion Code: 20-11 & 21-11 (version 2)					
Motion Description: low-five, walk CMU Motion Code: 20-12 & 21-12					
Motion Description: blind man's bluff (blindfold tag) CMU Motion Code: 20-13 & 21-13					
Motion Description: hold hands, swing arms, walk CMU Motion Code: 22-8 & 23-8					
Motion Description: synchronized jumping jacks CMU Motion Code: 22-16 & 23-16					
Motion Description: synchronized jumping jacks CMU Motion Code: 22-16 & 23-16 (version 2)					
Motion Description: synchronized jumping jacks CMU Motion Code: 22-16 & 23-16 (version 3)					

Table 4.1 (continued) Forms Created from Two People's Interaction

	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: walk; A catches keys thrown by B CMU Motion Code: 22-23 & 23-23					
Motion Description: walk; A catches wallet thrown by B CMU Motion Code: 22-25 & 23-25					

4.1.2 Forms Created from Different Human Walking Styles

The forms created from motions of stylized walks are shown in Table 4.2. The number of curves used in each form creation was five since there was a single subject. Although each form was created by choosing these five curves in the same order, the undulations on each form's surface are different. The reason behind this is that the way people walk reflects their emotional state and personality, so the created motion curves also reflect the different emotions, walking habits, and interpretations. The walking styles, such as fast or slow, sad or happy, confident or shy, scared or relaxed, created different isocurve patterns on the forms. How these isocurves are formed is explained in section 3.2.2. Widely or closely spaced distributions of the isocurves, differing from style to style, allowed the surfaces to take on varying sinuous forms. In Table 4.2, this variation can be read from the surface patterns formed by dark green regions representing the frame intervals when the motion was slow and light green regions representing the frame intervals when the motion was fast.

In addition, the reason for the patterned surfaces is that the change in the speed and position of the subject's limbs was repetitive during the performances.

Table 4.2 Forms Created from Human Walks in Different Styles

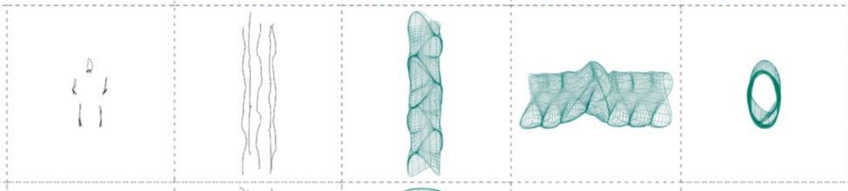
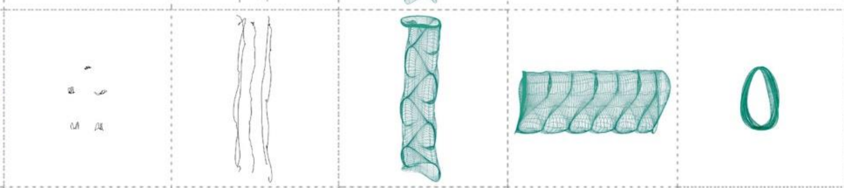
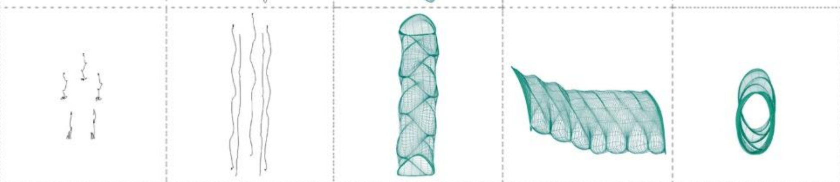
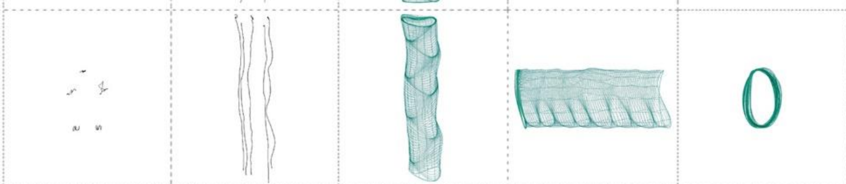
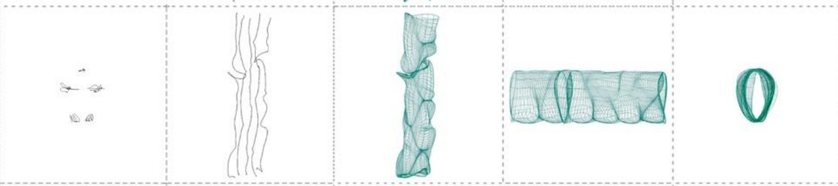
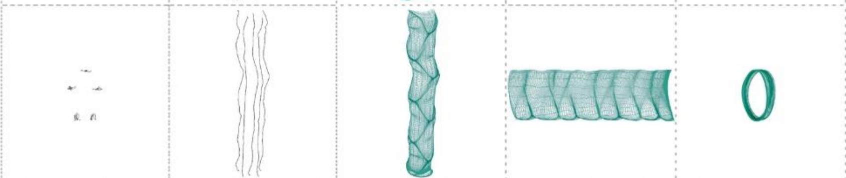
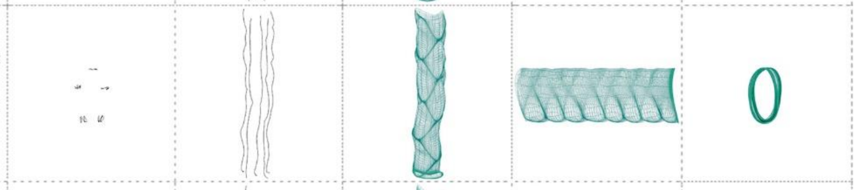
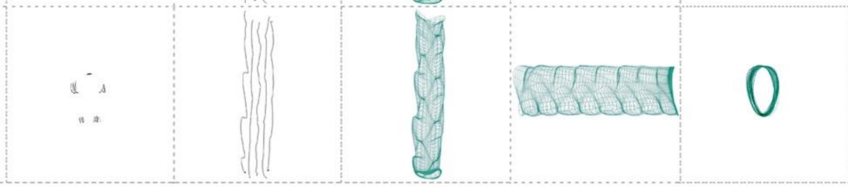
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: walk on uneven terrain CMU Motion Code: 36-1					
Motion Description: confident walk forward CMU Motion Code: 82-9					
Motion Description: walk forward and stepping up stairs CMU Motion Code: 83-35					
Motion Description: moonwalk CMU Motion Code: 90-32					
Motion Description: slow walk CMU Motion Code: 91-10					
Motion Description: too cool walk CMU Motion Code: 91-12					
Motion Description: sad walk CMU Motion Code: 91-13					
Motion Description: depressed walk CMU Motion Code: 91-14					
Motion Description: quick walk CMU Motion Code: 91-17					

Table 4.2 (continued) Forms Created from Human Walks in Different Styles

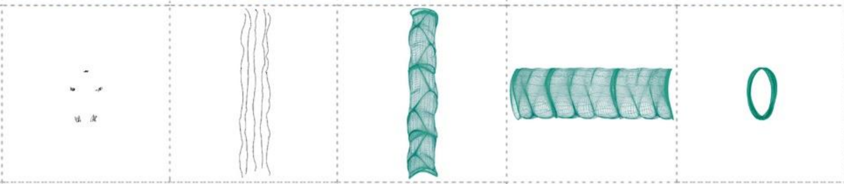
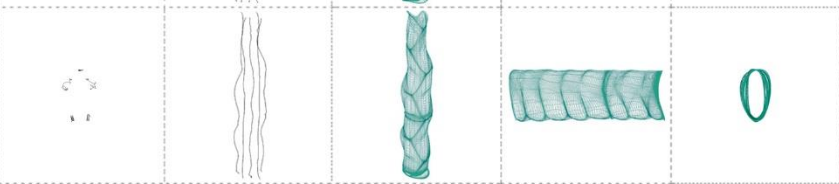
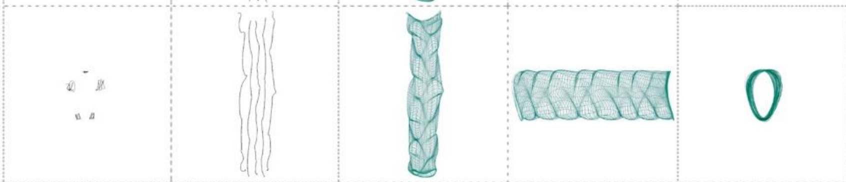
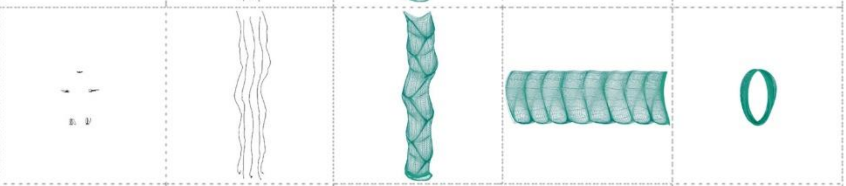
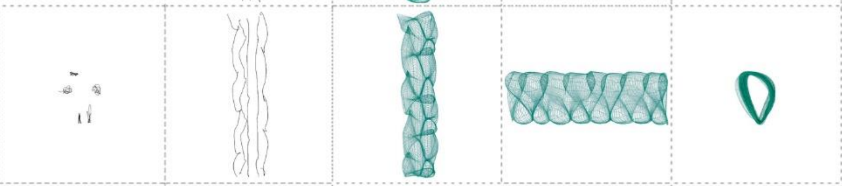
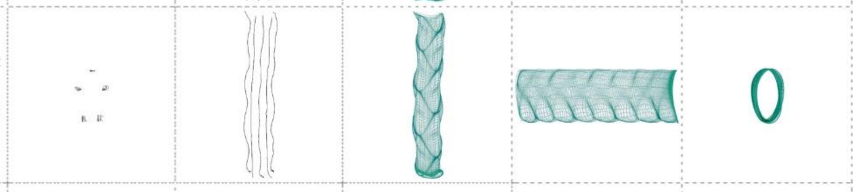
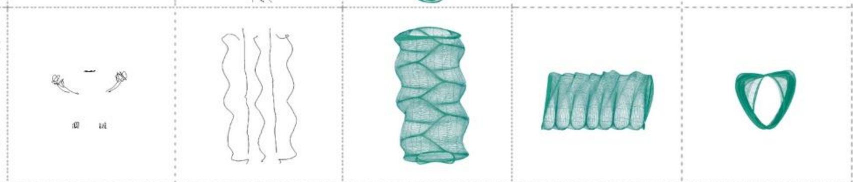
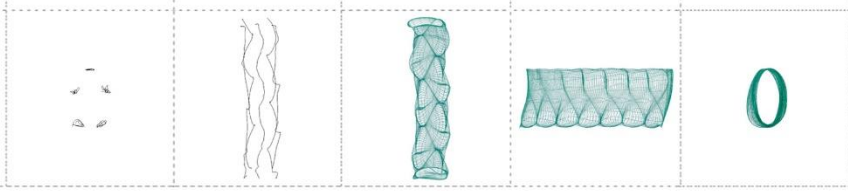
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: careful walk looking around CMU Motion Code: 91-18					
Motion Description: march CMU Motion Code: 91-19					
Motion Description: shy walk CMU Motion Code: 91-20					
Motion Description: casual quick walk CMU Motion Code: 91-22					
Motion Description: scared walk CMU Motion Code: 91-32					
Motion Description: macho walk CMU Motion Code: 91-33					
Motion Description: normal walk CMU Motion Code: 91-34					
Motion Description: walk with arms out, balancing CMU Motion Code: 132-1					
Motion Description: walk crossover CMU Motion Code: 132-16					

Table 4.2 (continued) Forms Created from Human Walks in Different Styles

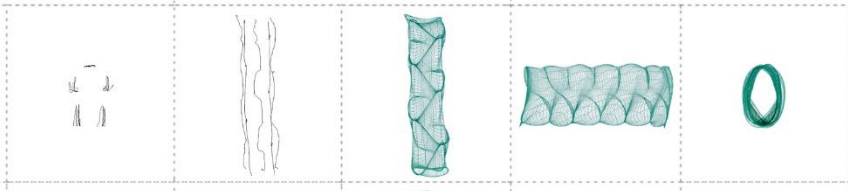
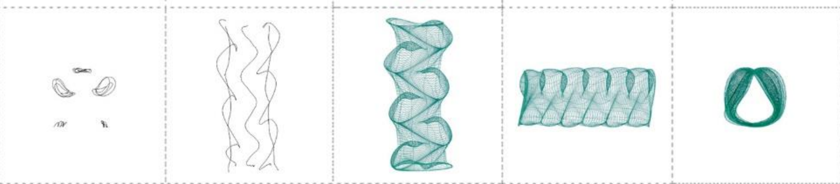
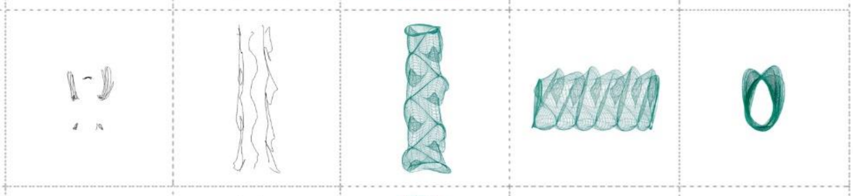
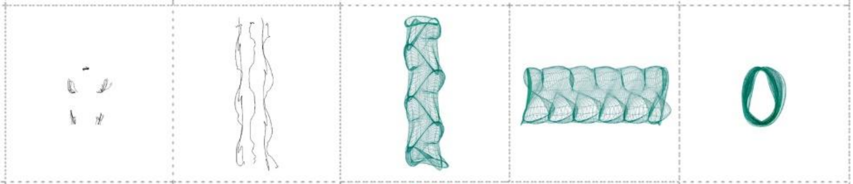
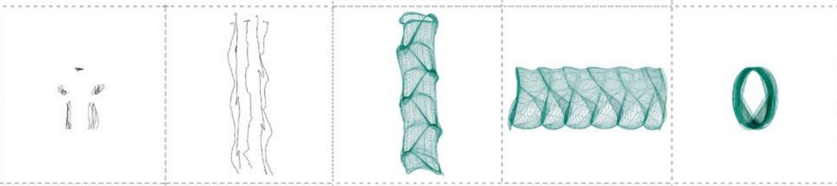
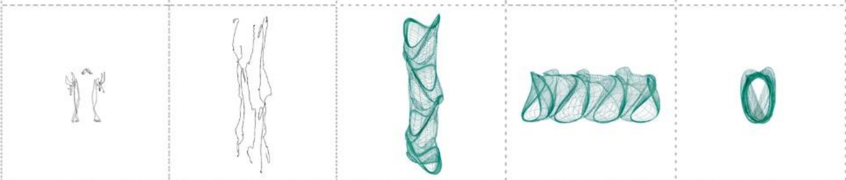
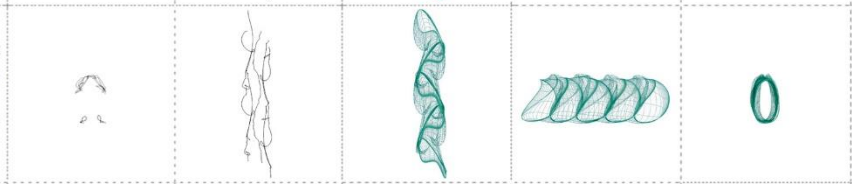
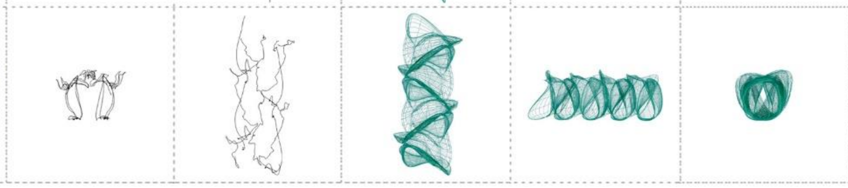
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: marching CMU Motion Code: 132-37					
Motion Description: walk swinging shoulders CMU Motion Code: 132-43					
Motion Description: walk with legs apart CMU Motion Code: 132-53					
Motion Description: walk with wild arms CMU Motion Code: 132-54					
Motion Description: walk with wild legs CMU Motion Code: 132-55					
Motion Description: walk with wild legs without swinging arms CMU Motion Code: 132-56					
Motion Description: martial arts walks (front kick) CMU Motion Code: 135-4					
Motion Description: martial arts walks (gedanbarai) CMU Motion Code: 135-5					
Motion Description: martial arts walks (mawashigeri) CMU Motion Code: 135-7					

Table 4.2 (continued) Forms Created from Human Walks in Different Styles

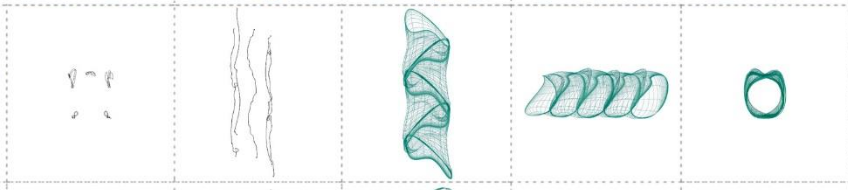
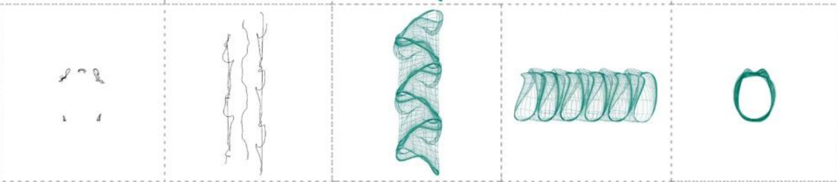
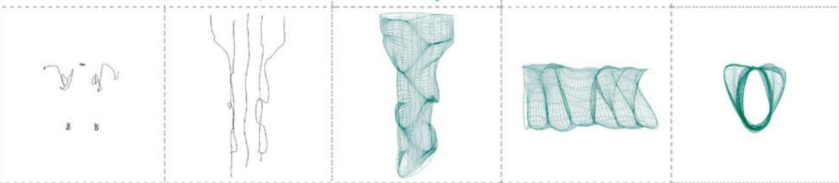
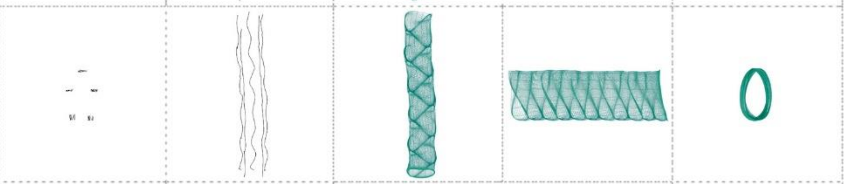
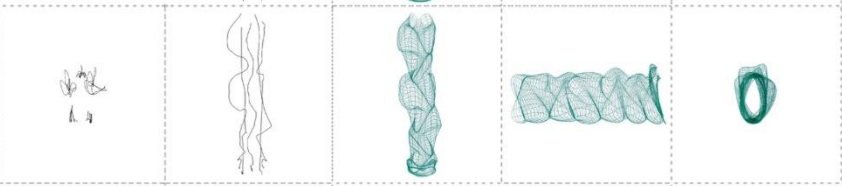
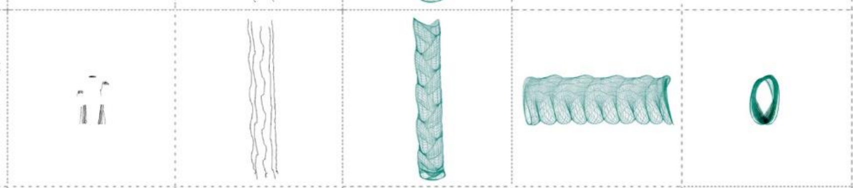
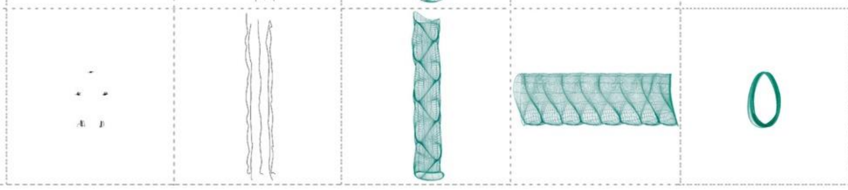
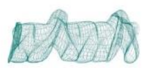
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: martial arts walks (oiduki) CMU Motion Code: 135-9					
Motion Description: martial arts walks (syutouuke) CMU Motion Code: 135-10					
Motion Description: walking while talking CMU Motion Code: 138-16					
Motion Description: cool walk CMU Motion Code: 142-4					
Motion Description: depressed walk CMU Motion Code: 142-5					
Motion Description: joy walk CMU Motion Code: 142-9					
Motion Description: lavish walk CMU Motion Code: 142-10					
Motion Description: marching CMU Motion Code: 142-11					
Motion Description: relaxed walk CMU Motion Code: 142-13					

Table 4.2 (continued) Forms Created from Human Walks in Different Styles

	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: rushed walk CMU Motion Code: 142-14					
Motion Description: sad walk CMU Motion Code: 142-15					
Motion Description: scared walk CMU Motion Code: 142-17					
Motion Description: shy walk CMU Motion Code: 142-19					
Motion Description: singing in the rain jump CMU Motion Code: 142-21					
Motion Description: sneaky walk CMU Motion Code: 142-22					
Motion Description: walk and step over CMU Motion Code: 143-15					

Some of these forms were created using the same or very similar motion scenarios, as shown in Table 4.3 in groups. However, different isocurve formations are observed on their surfaces because of the change of the person performing the motion. Which motion is performed by whom is indicated in letters in the relevant table. For example, the 'too cool walk' or 'sad walk' performed by the person indicated as 'G' differs from the person indicated as 'H' performing these motions regarding their speed and the position of their limbs during the motion. The reason for this is the changing personalities of people.

In addition, the same person performing the same scenario in different variations also created slightly different surface patterns (as in 'quick walk' and 'casual quick walk').

Table 4.3 Forms of Same or Similar Human Walking Styles Performed by Different People

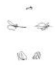
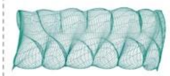
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: too cool walk CMU Motion Code: 91-12 Subject G					
Motion Description: cool walk CMU Motion Code: 142-4 Subject H					
Motion Description: sad walk CMU Motion Code: 91-13 Subject G					
Motion Description: sad walk CMU Motion Code: 142-15 Subject H					
Motion Description: depressed walk CMU Motion Code: 91-14 Subject G					
Motion Description: depressed walk CMU Motion Code: 142-5 Subject H					
Motion Description: shy walk CMU Motion Code: 91-20 Subject G					
Motion Description: shy walk CMU Motion Code: 142-19 Subject H					

Table 4.3 (continued) Forms of Same or Similar Human Walking Styles Performed by Different People

	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: quick walk CMU Motion Code: 91-17 Subject G					
Motion Description: casual quick walk CMU Motion Code: 91-22 Subject G					
Motion Description: rushed walk CMU Motion Code: 142-14 Subject H					
Motion Description: scared walk CMU Motion Code: 91-32 Subject G					
Motion Description: scared walk CMU Motion Code: 142-17 Subject H					
Motion Description: marching CMU Motion Code: 91-19 Subject G					
Motion Description: marching CMU Motion Code: 132-37 Subject I					
Motion Description: marching CMU Motion Code: 142-11 Subject H					

4.1.3 Forms Created from Various Expressions and Human Behaviors

The forms created from motions of various expressions and human behaviors are shown in Table 4.4. The number of curves used in each form creation was five, and their selection order was the same as in category 2-stylized walks.

However, unlike the previous category, sudden transitions are seen on the forms instead of a clear, repetitive pattern formation. The reason for this is that the speed and position changes of the subject's limbs were not repetitive but sudden. Therefore, the resulting motion curves do not have a rhythm. For instance, the transition of the 'run/jog, sudden stop' movement from a fast performance to a slow and finally stable position was reflected in the resulting form, which can be read from the dark green color becoming clear at the transition points (Table 4.4).

The motion curves without a rhythm made it possible to obtain very interesting forms. Even though the resulting forms are unshapely, this unshapeliness makes them unique and creates diversity.

Table 4.4 Forms Created from Various Expressions and Behaviors

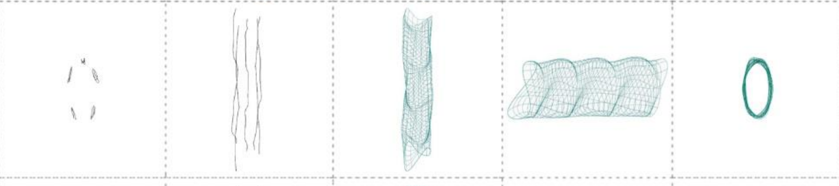
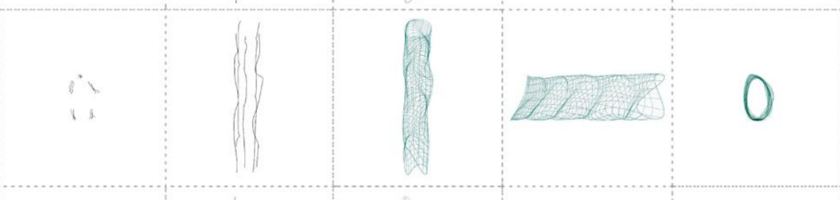
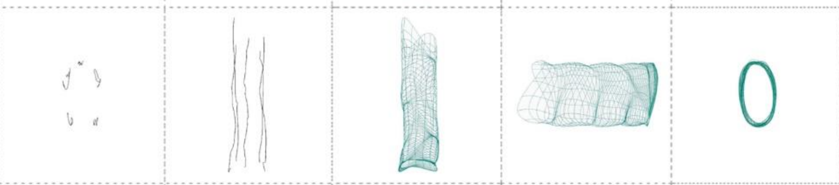
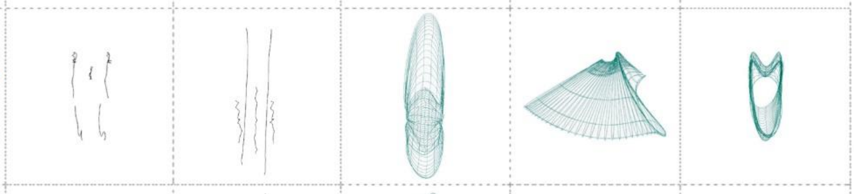
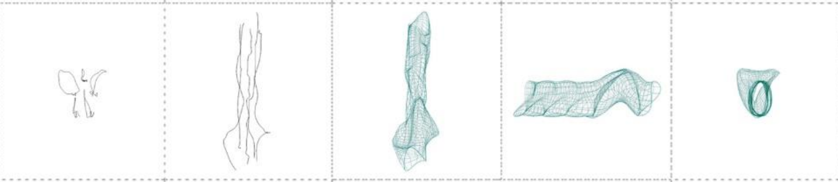
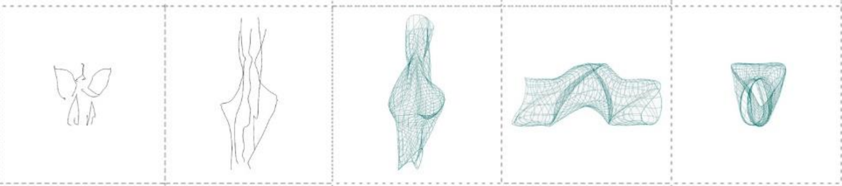
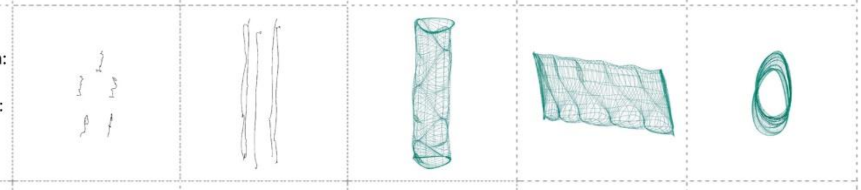
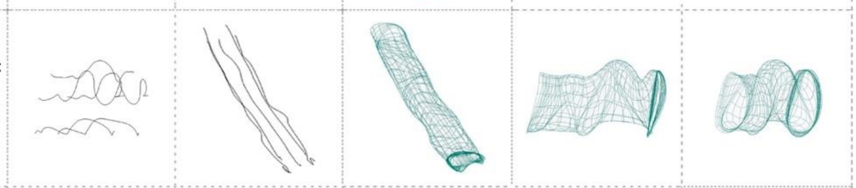
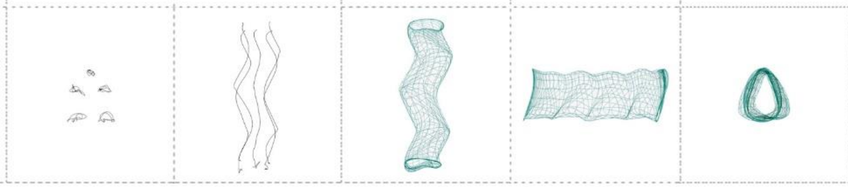
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: run/jog CMU Motion Code: 2-3					
Motion Description: run CMU Motion Code: 16-55					
Motion Description: run/jog, sudden stop CMU Motion Code: 16-57					
Motion Description: playground - grip bar, swing body CMU Motion Code: 43-3					
Motion Description: run, leap CMU Motion Code: 49-4					
Motion Description: run, leap CMU Motion Code: 49-5					
Motion Description: slope 1 CMU Motion Code: 74-14					
Motion Description: run jump CMU Motion Code: 75-2					
Motion Description: wide leg run CMU Motion Code: 75-4					

Table 4.4 (continued) Forms Created from Various Expressions and Behaviors

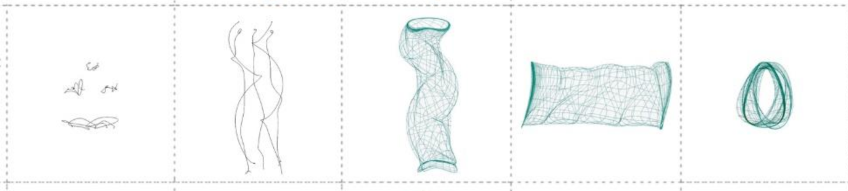
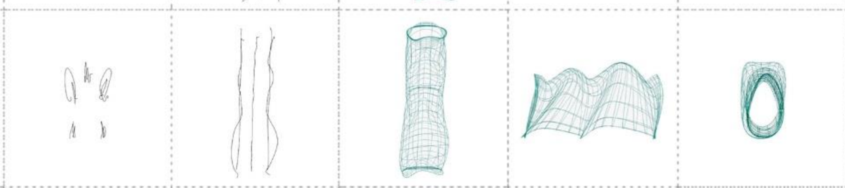
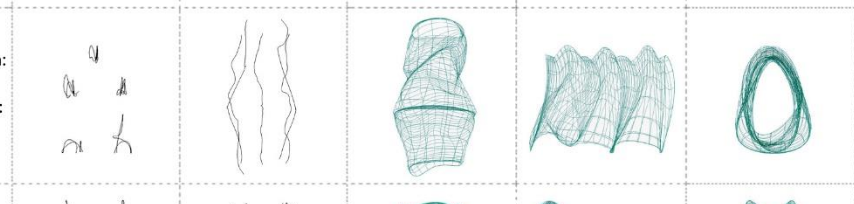
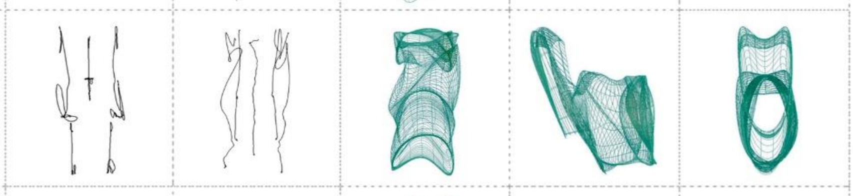
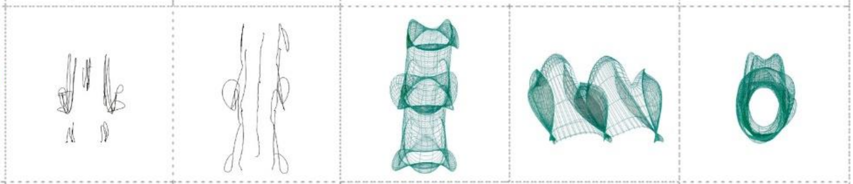
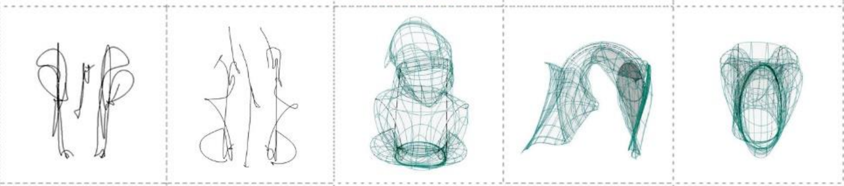
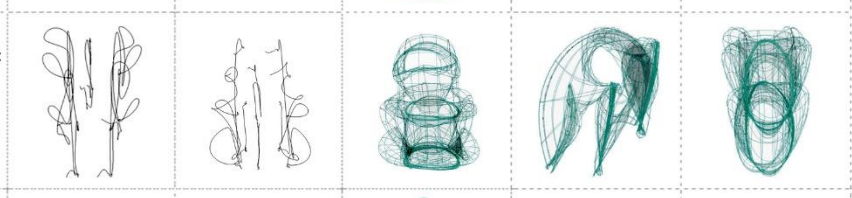
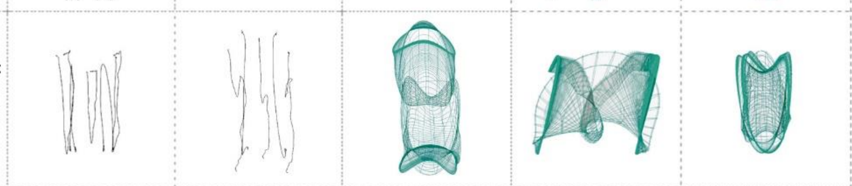
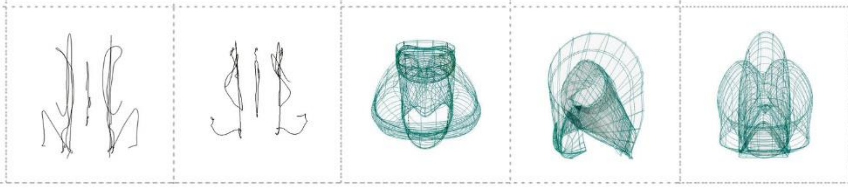
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: cross leg run CMU Motion Code: 75-5					
Motion Description: 2 jump CMU Motion Code: 75-11					
Motion Description: hopscotch CMU Motion Code: 75-13					
Motion Description: jump backwards off ledge CMU Motion Code: 81-13					
Motion Description: walking, swinging arms, stretching CMU Motion Code: 86-7					
Motion Description: backflip CMU Motion Code: 87-4					
Motion Description: backflips, jump onto platform CMU Motion Code: 88-2					
Motion Description: front hand flip CMU Motion Code: 90-15					
Motion Description: sequence CMU Motion Code: 90-29					

Table 4.4 (continued) Forms Created from Various Expressions and Behaviors

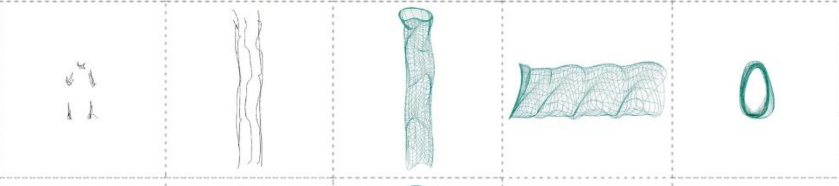
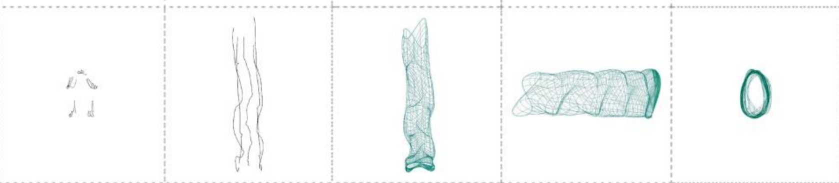
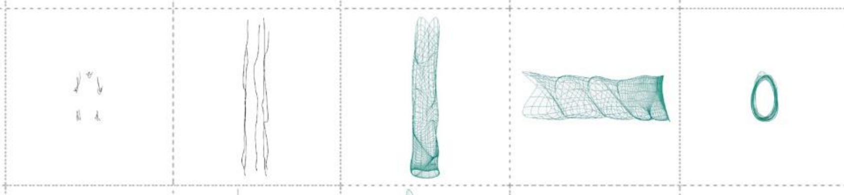
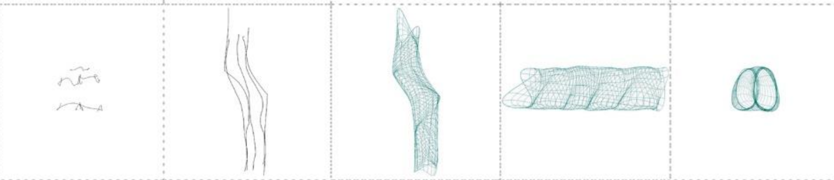
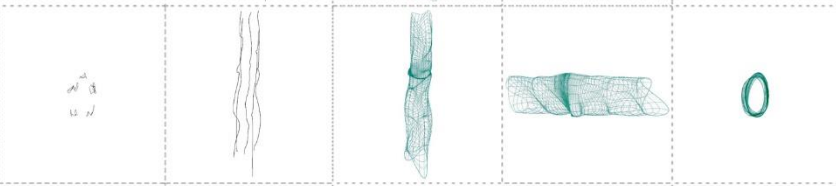
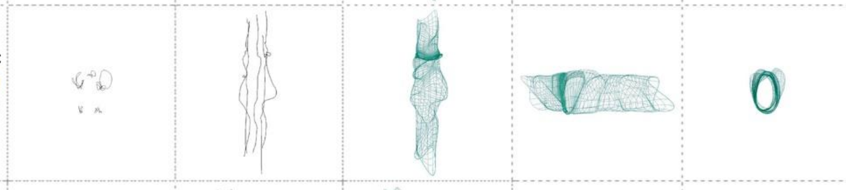
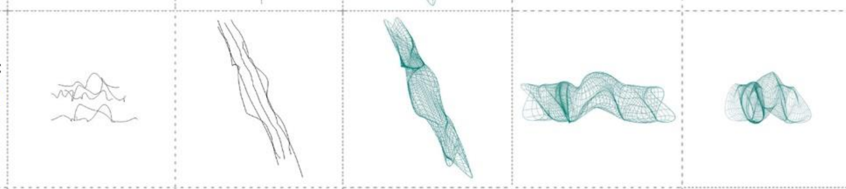
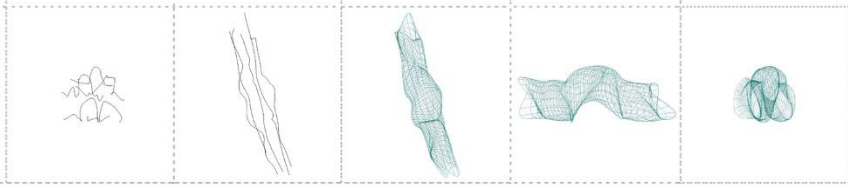
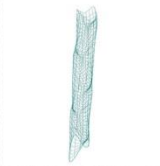
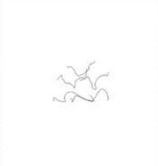
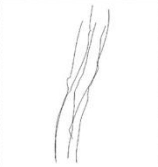
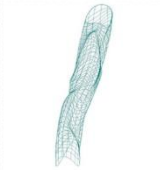
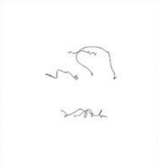
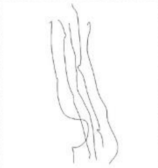
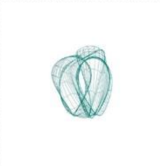
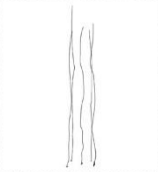
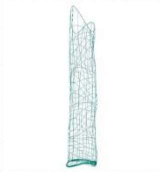
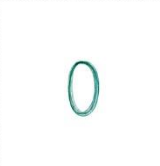
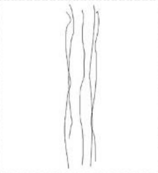
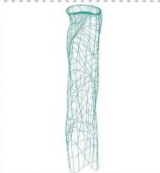
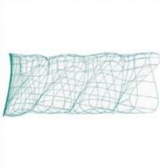
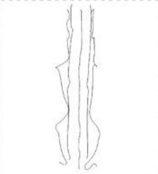
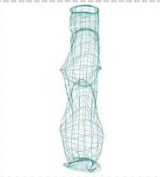
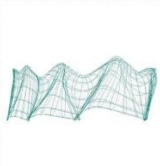
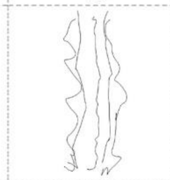
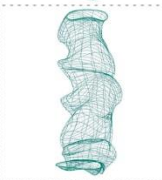
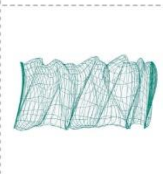
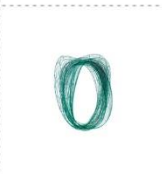
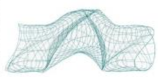
	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: start jog CMU Motion Code: 104-8					
Motion Description: start run CMU Motion Code: 104-55					
Motion Description: run stop CMU Motion Code: 104-57					
Motion Description: walk to run CMU Motion Code: 127-4					
Motion Description: run side step left CMU Motion Code: 127-13					
Motion Description: run stop run CMU Motion Code: 127-18					
Motion Description: run quick stop run CMU Motion Code: 127-19					
Motion Description: run jump stop run CMU Motion Code: 127-22					
Motion Description: run jump over CMU Motion Code: 127-25					

Table 4.4 (continued) Forms Created from Various Expressions and Behaviors

	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: run over CMU Motion Code: 127-36					
Motion Description: run duck under-neath CMU Motion Code: 127-38					
Motion Description: high five CMU Motion Code: 141-22					
Motion Description: run to stop CMU Motion Code: 143-2					
Motion Description: start to run CMU Motion Code: 143-3					
Motion Description: jumping distances CMU Motion Code: 143-5					
Motion Description: hopscotch CMU Motion Code: 143-31					

The forms created from the 'run, leap' motion type, particularly shown in Table 4.5, are different from each other as a result of being performed by the same person (named J) in different recordings because human-body motions are performed naturally depending on many factors such as state of body, state of mind, time and environment. They are not coded actions as in machines and do not always happen the same way. Each person's walking, running, sitting, standing, or jumping is different from another person, although the physiological methods are the same. Even the motions performed by the same person, for example, in different emotional states, are not the same; perhaps this was the case in the example shown in Table 4.5.

Table 4.5 Forms of Same Type Motion Style Interpreted Differently by the Same Person

	curves' front view	curves' top view	form's top view	form's left view	form's front view
Motion Description: run, leap CMU Motion Code: 49-4 Subject J					
Motion Description: run, leap CMU Motion Code: 49-5 Subject J					

As a result, every output of the research's first stage has different potentials due to the changing ingredients. Since the overall research aimed to combine MoCap technology with kinetic architecture to create personal space, obtaining a kinetic form over a sample motion form was tried to be achieved in the second part of the research, whose outputs were evaluated in the next section.

4.2 Results of Phase 2: Design of Deployable Personal Space

What kind of kinetic systems can be used to provide mobility to the obtained forms varies from one form to another, which, in the meantime, increases creativity in the architectural design process. An example method for deployable personal space design, conducted with the motion ‘high-five, walk’, led to the creation of a cable-suspended pavilion consisting of a tensile membrane structure, an external movable supporting structure, and foldable curving ramps allowing access to the suspended form.

The tensile membrane structure comprises curved steel cords, varying in undulation and irregularity, and a semi-transparent tensile material stretched between them, allowing a changing pattern of light and shadow when penetrated by light. The results of the design steps explained in Section 3.2.2 are shown in Figure 4.1.

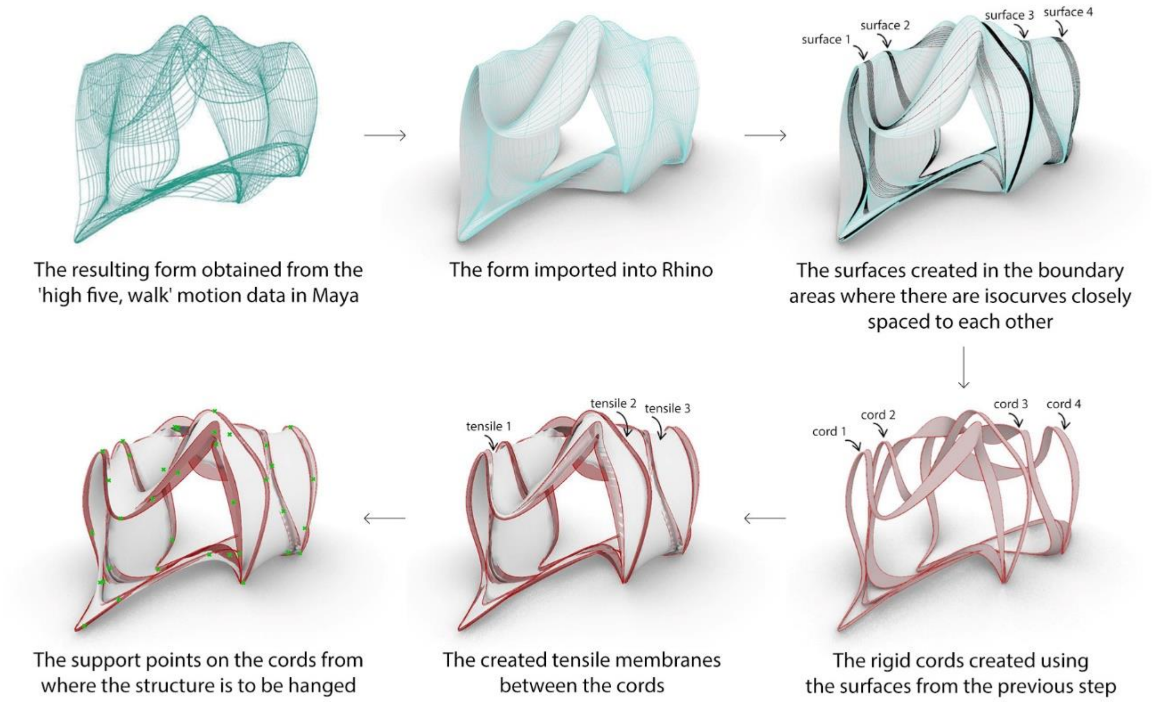


Figure 4.1. The Design Stages of the Tensile Membrane Structure

This tensile membrane structure is suspended to the surrounding supporting structure shown in Figure 4.2 from its structural cords by tensile steel cables. The supporting structure is in a tubular form and has both angulated and translational movement abilities thanks to its dual pantograph system made of wooden scissor bars and metal hinges; hence, it is deployable.

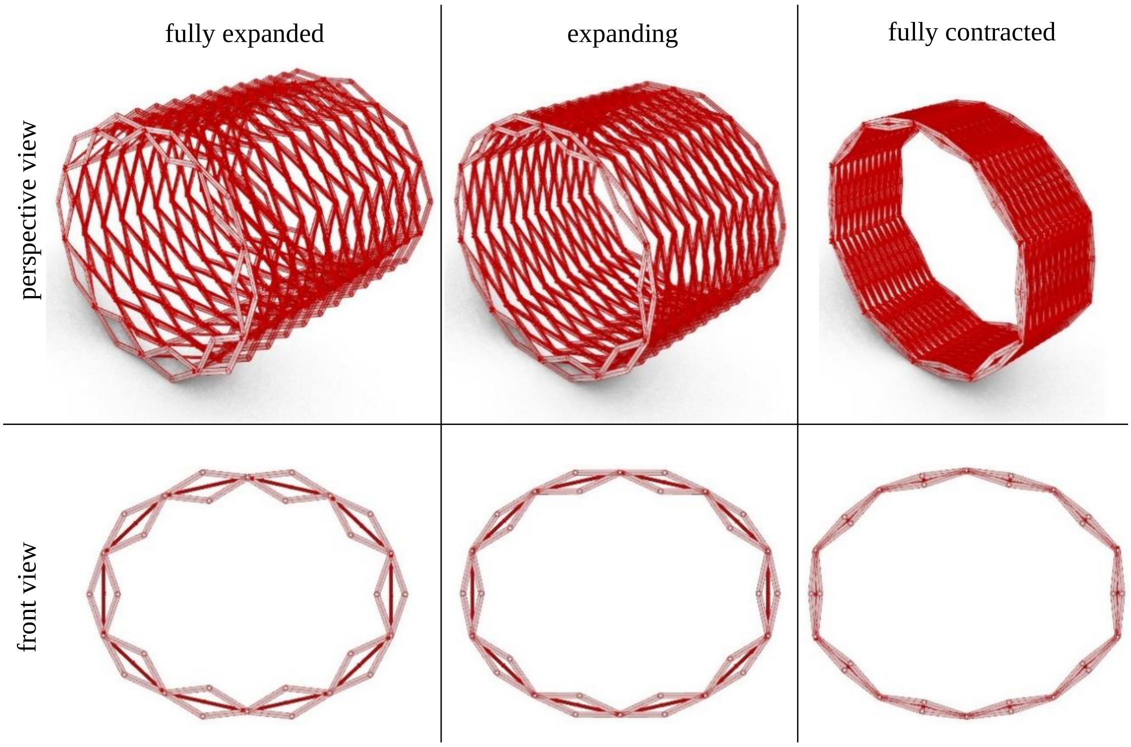


Figure 4.2. The Perspective and Front Views of the Exoskeletal Structure at Fully Expanded, Expanding, and Fully Contracted Configuration

At the end of this whole design method, the form obtained from human-body motion data was transformed into a kinetic model using a tensile membrane with a movable supporting structure system (Figure 4.3). The overall design can be folded up by applying pressure from both ends of the tubular structure. With the preferred materials and the kinetic systems, the sinuous nature of the internal form is revealed, and its mobility is enabled.

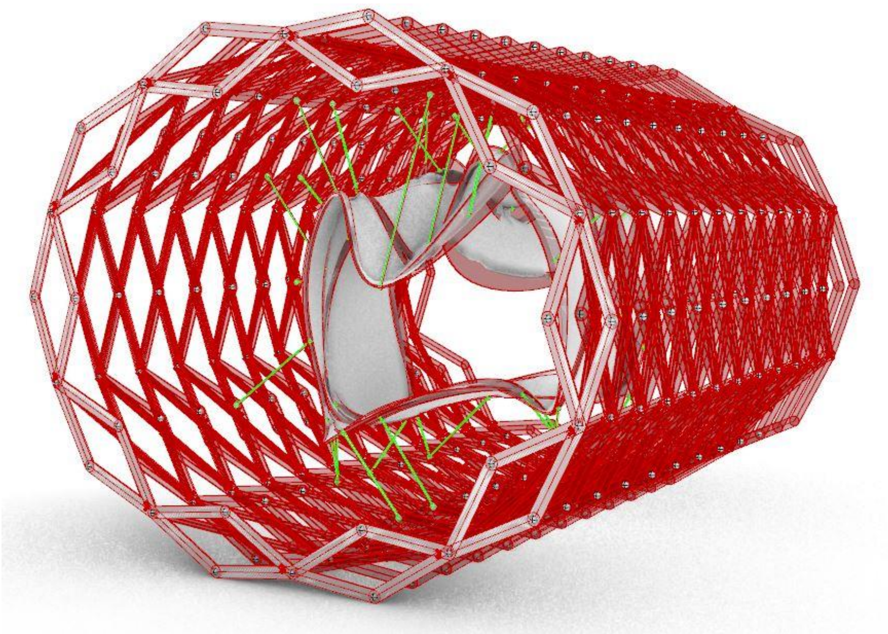


Figure 4.3. The Cable-Suspended Tensile Membrane Structure with a Movable Supporting Structure System

The pavilion can be easily transported to locations where there are crowds of people to offer personal space and installed on-site as it is lightweight and requires no foundation. It can be used by two people at a time for varying purposes such as relaxation, exhibition, or multimedia performance, then can be folded up if not needed. Thanks to occupying a small space when folded, it can be stored in a convenient place for subsequent uses (Figures 4.4 and 4.5).

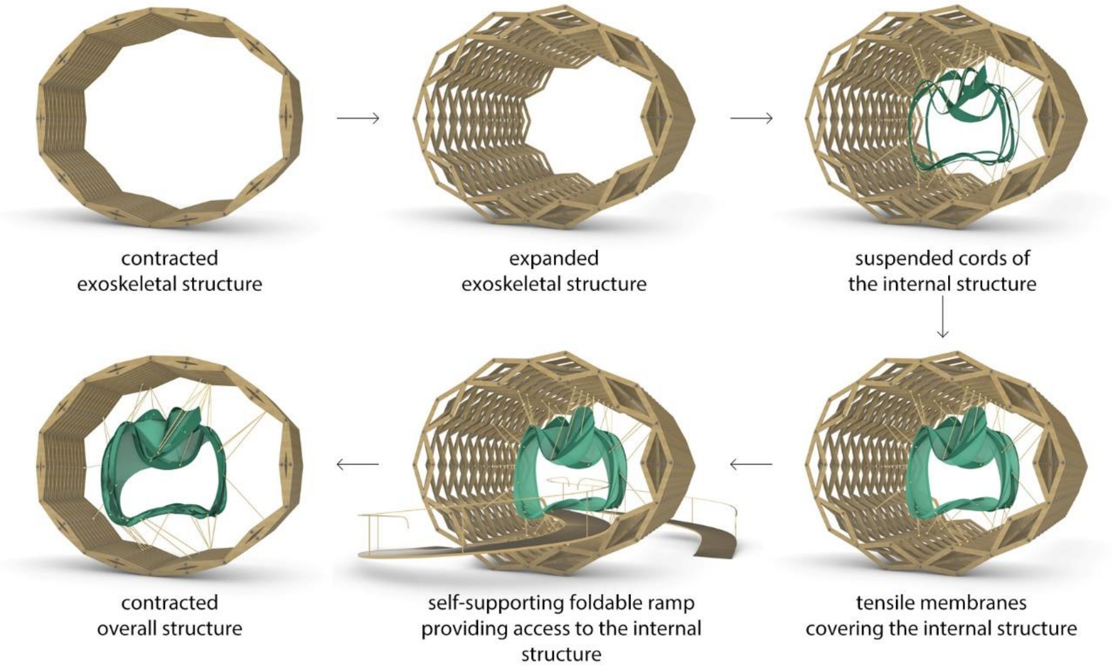


Figure 4.4. The Perspective Drawings Showing the Installation and Deployment Stages of the Cable-Suspended Pavilion

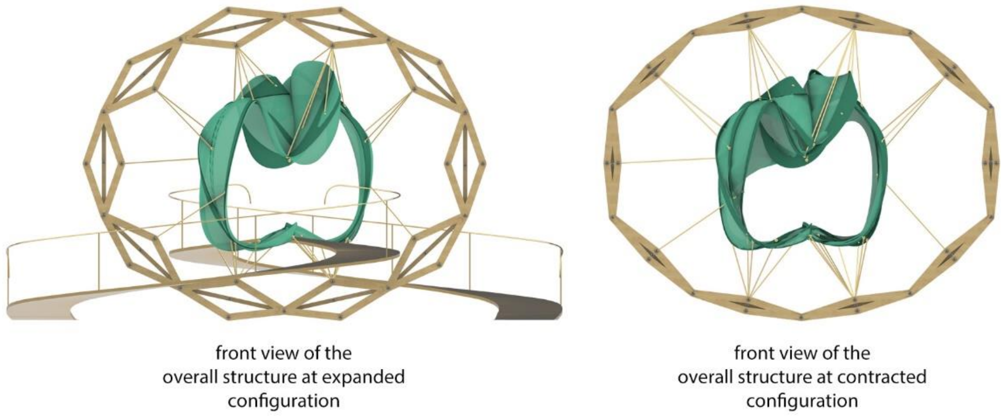


Figure 4.5. The Front Views of the Cable-Suspended Pavilion at an Expanded and Contracted Configuration

Thanks to using the parametric design method conducted in Grasshopper, the parameters such as the thickness and width of the scissor bars, the length and the size of the structure, and the number of rows of the main and sub-scissors are adjustable. Accordingly, the tubular system can also be used as an external supporting structure for other forms besides the form created from the 'high-five, walk' motion type. For instance, if the number of rows of the main and sub-scissors is reduced, it can be used to support the form of ‘marching’, as seen in Figure 4.6.

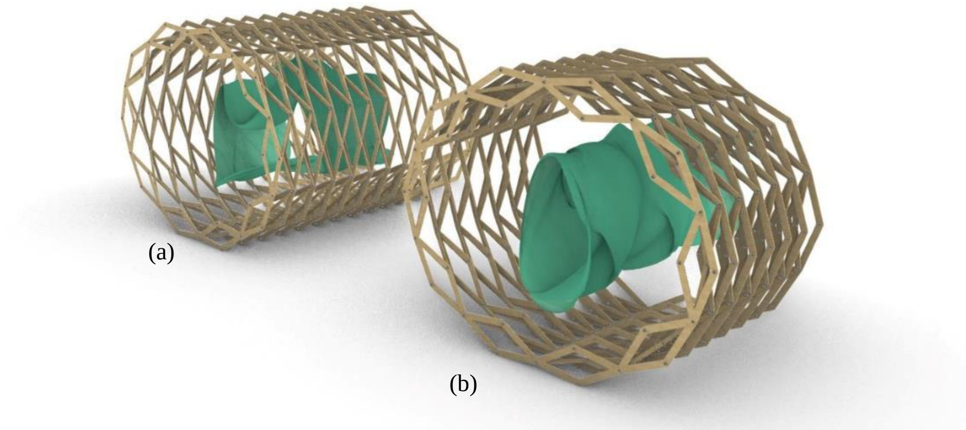


Figure 4.6. The Tubular System Design that can be Adjusted Depending on the Characteristics of the Motion Form to be Hung Inside. The Examples of ‘High-Five, Walk’ (a) and ‘Marching’ (b)

If the overall design is evaluated from ergonomic and proxemic perspectives in light of the information given in the literature, it can be pointed out that the resulting pavilion is fulfilling the requirements. How it has been achieved is explained below.

i. Evaluation from a proxemic point of view

The size, shape, and when or where can be needed of personal space vary depending on many factors, as explained in section 2.2. Therefore, an architectural personal space requires to be dynamic to adapt to the users’ preferences. Accordingly, it was aimed to design a space having semifixed-features that allow users to regulate the design. The resulting pavilion’s translation movement allows its length to be adjusted, providing personal space in different sizes for its users.

Moreover, the pavilions that can be obtained by application of the design method to different motion scenarios have the potential to create diverse personal spaces in different sizes and shapes. Thanks to their lightweight and deployable features, these pavilions can be moved and used in indoor or outdoor environments where personal space is needed.

On the other hand, since the design is formed by embodying human-body motion, it contains the personal distance indicated by proxemics in its essence. The boundary surface covering the trajectories of motion naturally creates the minimum acceptable personal space size. This can also be defined as personal distance swept volume referring to the 'human swept volume' concept explained in section 2.2.2.3.

ii. Evaluation from an ergonomic point of view

Personal spaces should be usable by the majority of the population; hence, they should be adjustable or produced in various sizes. In order to achieve this, a parametric design has been made, the parameters of which can be changed in accordance with the user population.

Finally, a 1/20 scale physical model was also made to test the movement mechanism of the pavilion as well as to observe its light and shadow conditions (Figure 4.7). While the movement of the exoskeletal structure was carried out smoothly, a disruption was observed in the movement of the inner structure’s cords caused by friction. Therefore, tensile membranes, cables, and cords with slippery coatings can be used in the pavilion to overcome this problem.

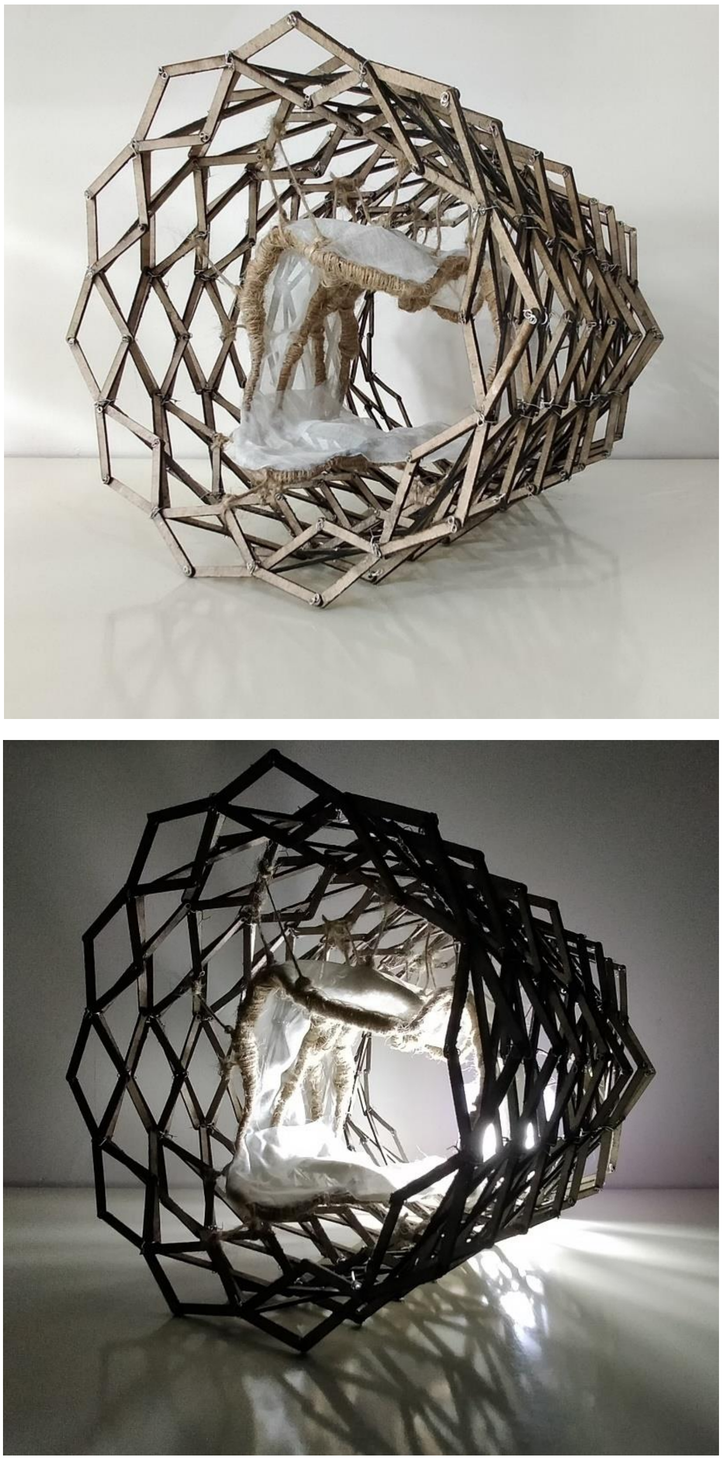


Figure 4.7. The Physical Model of the Cable-Suspended Pavilion in Daytime and Nighttime

CHAPTER 5

CONCLUSION

The subject of this thesis stems from a personal interest in the relationship between movement and architecture. It is focused on what kind of contributions movement provides to architecture and how. Although movement has been intertwined with architecture since ancient times, the idea of utilizing real movement data in design is not common. Hence, this topic has been found worthy of investigation and has driven the research toward studying both movement as a design ingredient and how movement is handled in kinetic architecture. While researching these issues, it was detected that there is a potential to integrate human-body movement data into kinetic architecture in order to provide a new perspective on flexible, adaptable, and transformable architectural form experimentation.

The main goal of the research was to understand how human beings can give shape to their environment through movement. For this, it was necessary to analyze movement to be used as a design ingredient. However, since movement happens in time and space and disappears the moment it is finished, it is hard to make these analyses. At this point, taking advantage of simulation techniques, which provide a demonstration of the way movement is perceived, comes into play. Simulation of motion has already made progress in different disciplines, and adapting their technology to architecture became essential for this research to reach its goal. One of these simulation techniques is MoCap which was given the most emphasis in this research.

Additionally, the research aimed to use the forms to be shaped by human movements as personal spaces because a personal space involves dynamism in it, like in movement; its size and shape can change depending on many factors such as cultural aspects, individual personalities, and the conditions of the environments. Also, it is well-suited to be constructed with kinetic systems.

Accordingly, the literature review section explored the history of movement simulation, various technologies used in simulating human-body movement, MoCap technology, the concept of personal space, and kinetic architecture in order to provide relevant information about the historical and current context of using movement in architecture.

After reviewing various technologies used in simulating movement, the optical marker-based MoCap system stood out as being the most preferred one in most studies reported in the literature as it provides precise and accurate data. The researchers obtained the movement data either by directly capturing them, letting students capture them through workshops, or using existing movement databases. Setting up a suitable environment for the use of optical MoCap systems, calibrating cameras, and dealing with problems such as glare and occlusion is a difficult process. It also takes a long time to edit the data afterward. Therefore, it was decided to use an existing database, CMU-GL Mocap Database, in this research.

Furthermore, most of the researches in the literature focused on transforming the movement data into forms to explore the generation of complex shapes that are difficult to obtain with usual design methods. In this process, the data of dance performances were used the most. However, in dance performances, the vast majority of the captured movements have intersecting trajectories. Dealing with such data is complicated and creates forms that might not be functional on an architectural scale. Instead, movement scenarios other than dance, having less overlapping trajectories, were found to be more beneficial for this study.

In addition, instead of using the movement data of all body joints, it was decided to use only the data of head, hands, and feet, which can give the form the greatest swept volume than other joints while causing minimal trajectory overlaps.

The process of obtaining a 3D form from human MoCap data, constituting the first phase of the research, was applied for all movement data included in the research material, and the criteria that ensured the diversity of the created forms were evaluated on a category basis. Converting a 3D form, selected among the outputs of the first phase, into a deployable personal space constituted the second phase of the research. As a result, a cable-suspended pavilion was designed. This pavilion has an internal structure created from motion and an external structure in which the internal structure is hung. The external structure supports the necessary movement ability of the pavilion to adapt to the dynamism of the personal space. It also emphasizes the form of motion and draws attention to it. Users can experience the space via a ramp from one end of the pavilion to the other. The pavilion can host physical or digital exhibitions and multimedia performances and can be used for relaxation.

Finally, regarding the subject matters presented in this thesis, it can be concluded that movement, which is an indispensable element of life and one of the bases of architecture, has more potential waiting to be explored. In order to make to most use of it in architecture, it is essential to embrace an interdisciplinary approach and utilize their advancements. This thesis, combining motion capture, personal space, and kinetic systems, aspired to enrich creativity in the kinetic form-finding process by utilizing 3D human movement data as a design ingredient. The revealed exciting trajectories and unusual forms of the nearly 100 movement types can be a source for future studies on the use of space, spatial experience, and human behaviors. Besides, the design method applied to an example pavilion design may be repeated for other movement types, and analysis can be made on their advantages and disadvantages.

REFERENCES

Achten, H. (2019). Interaction narratives for responsive architecture. *Buildings, 9*(3). doi:10.3390/buildings9030066

Aguiar, D. V. (2018). *Space, body and movement, Notes on the research of spatiality in architecture.* Retrieved January 18, 2022, from https://www.researchgate.net/publication/327164114_SPACE_BODY_AND_MOVEMENT_notes_on_the_research_of_spatiality_in_architecture

Anonymous. (2019). *Çalışma yeri düzenlemede ergonomi [Ergonomics in workplace arrangement]* [PDF]. Kırıkkale University. Retrieved May 17, 2023, from https://panel.kku.edu.tr/Content/enformatik/%C4%B0SG/ergonomi_antropometri_2019.pdf

Asefi, M., & Aram, S. (2018). Flexibility in architecture: An Innovative Design for Covering of a Transformable Dome Using Kinetic Elements. *Space Ontology International Journal, 7*(4), 41–52.

Athias, D. (2020, January 02). Generating curves from motion trails in Maya. Retrieved May 11, 2021, from: https://www.delanimation.com/tutorials-1/2020/1/2/generating-curves-from-motion-trails-in-maya

Bernstein, R., Shafir, T., Tsachor, R., Studd, K., & Schuster, A. (2015). Laban movement analysis using kinect. *International Journal of Computer, Electrical, Automation, Control and Information Engineering, 9*(6), 1574–1578.

Berrones, A. (2007, December 27). *Personal Space*. Yanko Design - Modern Industrial Design News. Retrieved April 9, 2023, from https://www.yankodesign.com/2007/12/26/personal-space/

Bieniek, Z. (2015). Examples of cable-bar modular structures based on the class-theta tensegrity systems. *Journal of Civil Engineering and Architecture, 9*(12). doi:10.17265/1934-7359/2015.12.007

Bingham-Hall, J. & Cosgrave, E. (2019). Choreographing the city: Can dance practice inform the engineering of sustainable urban environments?, *Mobilities*, 14:2,188-203, doi:10.1080/17450101.2019.1567981

Boradkar, P. (2010). Designing things: a critical introduction to the culture of objects. Berg Publishers, Oxford, U.K., Retrieved April 8, 2023, from https://www.academia.edu/11708978/Introduction_Designing_Things

Carnegie Mellon University graphics lab, motion capture library. (n.d.). Retrieved May 11, 2021, from: http://mocap.cs.cmu.edu/resources.php

Davis, T. A., & Altevogt, R. (1979). Golden Mean of the Human Body. *Fibonacci Quarterly, 17*(4), 340-(344). http://library.isical.ac.in:8080/xmlui/bitstream/handle/10263/1436/TFQ-17-4-1979-P340-344.pdf?sequence=1&isAllowed=y

Dempster, W. T., Gabel, W. C., & Felts, W. J. (1959). The anthropometry of the manual work space for the seated subject. *American journal of physical anthropology, 17*(4), 289–317. https://doi.org/10.1002/ajpa.1330170405

Destro, N. (2009, August 12). *Personal space protector in Braamfontein*. Nathan Destro's Photo Blog. Retrieved April 11, 2023, from https://nathandestro.wordpress.com/2009/08/23/personal-space-protector-in-braamfontein/

Diniz, N. (2008). Body tailored space: Configuring space through embodiment. CAADRIA 2008 - *The Association for Computer-Aided Architectural Design Research in Asia: Beyond Computer-Aided Design*, 510–517.

Ebenreuter, N. (2005). Dance movement: A focus on the technology. IEEE *Computer Graphics and Applications, 25*(6), 80–83. https://doi.org/10.1109/MCG.2005.127

Elkhayat, Y. O. (2014). Interactive movement in kinetic architecture. *JES. Journal of Engineering Sciences, 42*(3), 816–845. doi:10.21608/jesaun.2014.115027

Forrest, B. & Schlage, T. (2018, August 10). Make center line for Maya, Retrieved May 11, 2021, from: http://forrest-schlage.blogspot.com/2018/08/makecenterline-for-maya.html

Fouad, S. M. (2012). Design methodology: Kinetic architecture (Master's thesis, Alexandria University, 2012). Alexandria University. Retrieved November 25, 2020, from https://www.academia.edu/4485555/Design_Methodology_Kinetic_Architecture

Fox, M. A. (2001). Ephemeralization, *Oz, 23*. doi:10.4148/2378-5853.1364

Fox, M. A. (2003). Sustainable applications of intelligent kinetic systems. *Transportable Environments 2*, 163–186.

Fox, M. A., & Yeh, B. P. (2000). Intelligent Kinetic Systems in Architecture. *Managing Interactions in Smart Environments*, 91–103. doi:10.1007/978-1-4471-0743-9_9

Gobetto, M. (2014). Work Analysis and Labour Productivity Evaluation Criteria. In: *Operations Management in Automotive Industries.* Springer Series in Advanced Manufacturing. Springer, Dordrecht, pp 87–113 https://doi.org/10.1007/978-94-007-7593-0_4

Goti, K. & Morse, C. (2021). Sky gazing tower. In S. Eloy, A. Kreutzberg & I. Symeonidou (Eds.). *Virtual aesthetics in architecture: Designing in mixed realities.* (1st ed., pp. 209-211). Routledge. doi:10.4324/9781003183105-36

Griesbeck, C. (n.d.). Introduction to labanotation. Retrieved January 28, 2022, from https://user.uni-frankfurt.de/~griesbec/LABANE.HTML

Hall, T. E. (1990). The Hidden Dimension. Doubleday Anchor Book Inc.

Hansen, L. A., & Morrison, A (2014). Materializing movement—Designing for movement-based digital interaction. *International Journal of Design, 8*(1), 29-42.

Harris, Y. (2002). Architecture and motion : Ideas on fluidity in sound, image and space. *Proc. of the Symp. on Systems Research in the Arts 2002*.

Heiner, R. (2012, July 18). New working environments: personal space - *Bene*. Retrieved April 6, 2023, from https://web.archive.org/web/20170506122327/http://bene.com/en/office-magazine/new-working-environments-personal-space

Henriques, G. C., Sousa, J. P., Gomez-Zamora, P., & Achten, H. (2020). Architecture in the age of the 4th industrial revolution. *International Journal of Architectural Computing, 18*(4), 317–319. doi:10.1177/1478077120950939

Hey, J. (n.d.). *Proxemics*. Sketchplanations. Retrieved April 9, 2023, from https://sketchplanations.com/proxemics

Hirschberg, U., Sayegh, A., Frühwirth, M., & Zedlacher, S. (2006). 3D motion tracking in architecture: turning movement into form - emerging uses of a new technology. Communicating Space(s) - 24th ECAADe Conferance Proceedings, 114–121.

Ilerisoy, Z. Y., Pekdemir-Basegmez, M. (2018). Conceptual research of movement in kinetic architecture. *Gazi University Journal of Science, 31*(2), 342–352. Retrieved from: https://dergipark.org.tr/en/download/article-file/481731

İslamoğlu, Ö., & Usta, G. (2018). Mimari tasarımda esneklik yaklaşımlarına kuramsal bir bakış [Theoretical overview of flexibility approaches in architectural design]. *The Turkish Online Journal of Design Art and Communication, 8*(4), 673–683. Retrieved from: http://dergipark.gov.tr/tojdac/issue/39502/466005

Itami, R. M. (2002). Estimating capacities for pedestrian walkways and viewing platforms. In *A report to Parks Victoria 20* (Issue June, p. 13).

Jensenius, A. R. (2007). Action – Sound, Developing methods and tools to study music-related body movements. *Musicology, 84*(2), 275. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Action-Sound:+Developing+Methods+and+Tools+to+Study+Music-related+Body+Movement#0

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics 14*(2), 201–211.

Jungjohann, H., & Woodington, W. (2016). Ontario celebration zone pavilion: A large pneumatic structure. *Procedia Engineering, 155,* 507–515. doi:10.1016/j.proeng.2016.08.054

Karasu, B. (2019). Bir otomotiv firmasında yalın üretim odaklı montaj hattı iyileştirme çalışmaları [Assembly line improvement studies of an automotive firm using lean manufacturing], (Master's thesis), Bursa Uludağ University, Retrieved May 17, 2023, from http://hdl.handle.net/11452/11490

Kırkan, S. & Çağdaş, G. (2019). Dans hareketi verilerinin sayısal ortamda forma dönüştürülmesi [Transformation of dance motion data to form through the computational environment]. *JCoDe: Journal of Computational Design, 1*(1), 11-34. Retrieved from: https://dergipark.org.tr/en/download/article-file/964110

Kırkan, S. (2015). Dans hareketi verilerinin sayisal ortamda forma dönüştürülmesi, [Transformation of dance motion data to form through the computational environment] (Master's thesis). Istanbul Technical University. Retrieved November 18, 2022, from https://polen.itu.edu.tr/xmlui/handle/11527/13120

Kronenburg, R. (2007). Flexible: Architecture that responds to change, Laurence King, United Kingdom.

Lauria, S., & Harwin, W. (2000). Managing Interactions in Smart Environments. In Managing Interactions in Smart Environments (Issue January 2000). 91–103. doi:10.1007/978-1-4471-0743-9

Loke, L., & Robertson, T. (2013). Moving and making strange: An embodied approach to movement-based interaction design. *ACM Transactions on Computer-Human Interaction, 20*(1). https://doi.org/10.1145/2442106.2442113

Longstaff, J.S. (1996). Cognitive structures of kinesthetic space reevaluating Rudolf Laban's choreutics in the context of spatial cognition and motor control [PDF]. (Unpublished Doctoral thesis, City University London). Retrieved May 17, 2023, from https://openaccess.city.ac.uk/id/eprint/11876/

Louw, M. (2016). The architectural promenade and the perception of time. *South African Journal of Art History, volume 31, number 2, 2016*. Retrieved from https://www.researchgate.net/publication/342657325_The_architectural_promenade_and_the_perception_of_time

Mahdavi, A. (2005). Space, Time, Mind. In: *Martens, B., Brown, A. (eds) Computer Aided Architectural Design Futures 2005*. Springer, Dordrecht. https://doi.org/10.1007/1-4020-3698-1_2

Marquardt, N. & Greenberg, S. (2011). Informing the design of proxemic interactions. *IEEE Pervasive Computing, 11*(2), pp. 14-23, Feb. 2012, doi:10.1109/MPRV.2012.15.

Marquardt, N., Hinckley, K. & Greenberg, S. (2012). Cross-device interaction via micro-mobility and f-formations. In Proceedings of the ACM. doi:10.1145/2380116.2380121

Matsushima, S., Sasaki, D. & Takenaka, R. (2007). Embodying architectural form and space by coupling computer and human performance using motion capture technology. *Em'Body'Ing Virtual Architecture*, 757–766.

Metatopia Studio. (2014, November 19). Metabody. https://metabody.eu/metatopia/#prettyPhoto

McQuarrie, L. (2014, October 14). *Interactive public plazas*. TrendHunter.com. Retrieved April 9, 2023, from https://www.trendhunter.com/trends/public-architecture

Meagher, M. (2015). Designing for change: The poetic potential of responsive architecture. *Frontiers of Architectural Research, 4*(2), 159–165. doi:10.1016/j.foar.2015.03.002

Megahed, N. A. (2016). Understanding kinetic architecture: Typology, classification, and design strategy. *Architectural Engineering and Design Management*, *13*(2), 130–146. doi:10.1080/17452007.2016.1203676

Misi, G., (2007). An algebraic representation of Labanotation for retrieval and other operations. *The 25th Biennial Conference of ICKL*. Retrieved from http://www.labanatory.com/common/download/2007ICKL/LNrepr.pdf

Namazian, A. & Mehdipour, A. (2013). Psychological demands of the built environment, privacy, personal space and territory in architecture. *International Journal of Psychology and Behavioral Sciences 2013, 3*(4): 109-113. doi:10.5923/j.ijpbs.20130304.04

Neville, R. M., & Scarpa, F. (2015). Design of shape morphing cellular structures and their actuation methods. *26th International Conference on Adaptive Structures and Technologies, ICAST 2015, October*. doi:10.13140/RG.2.1.4530.1527

Neville, R. M., Scarpa, F., & Pirrera, A. (2016). Shape morphing Kirigami mechanical metamaterials. *Scientific Reports*, *6*(August 2015), 1–12. doi:10.1038/srep31067

Özgenel, F. ve Gönenç Sorguç, A. (2011). Sayısal ortamda tasarımın deneyimlenmesi için arayüzlerin geliştirilmesi: Bir ön-tasarım parametresi olarak ses [Developing an interface in performance based computational design: Acoustical performance of preliminary designs]. *Metu Journal of The Faculty of Architecture, 28* (2), 243-253, Ankara, Türkiye.

Pheasant, S. & Haslegrave, C. (2018). *Bodyspace* (3rd ed.). CRC Press. https://www.perlego.com/book/1574258/bodyspace-anthropometry-ergonomics-and-the-design-of-work-third-edition-pdf

Piedade Ferreira, M. (2003). *Moving towards well-being: A phenomenological approach in computation to explore the body as an architectural tool*. 1–2.

Piedade Ferreira, M., de Mello, D. C., & Duarte, J. P. (2011). The grammar of movement: A step towards a corporeal architecture. *Nexus Network Journal, 13*(1), 131–149. https://doi.org/10.1007/s00004-011-0058-4

Qu, H., Fang, Y., & Guo, S. (2015). Theory of degrees of freedom for parallel mechanisms with three spherical joints and its applications. *Chinese Journal of Mechanical Engineering (English Edition), 28*(4), 737–746. https://doi.org/10.3901/CJME.2015.0116.049

Ramzy, N., & Fayed, H. (2011). Kinetic systems in architecture: New approach for environmental control systems and context-sensitive buildings. *Sustainable Cities and Society, 1*(3), 170–177. doi:10.1016/j.scs.2011.07.004

Schumacher, M., Schaeffer, O. & Vogt, M.M. (2010) Move: Architecture in motion- Dynamic components and elements, Birkhauser, Germany

Šenk, P. (2013). The Concept of Capsule Architecture as Experiment: Origins and Manifestations with Selected Examples from Slovenia and Croatia. *Prostor, 21*(2), 351–361. Retrieved from: https://www.academia.edu/34732180/The_Concept_of_Capsule_Architecture_as_Experiment_Origins_and_Manifestations_with_Selected_Examples_from_Slovenia_and_Croatia

Sevaldson, B. (2005). Developing digital design techniques: Investigations on creative design computing (Doctoral Thesis). The Oslo School of Architecture and Design (AHO)

Sheldon, J. L. (1989). Production and design of the Harold Tovish: Sculptor and Eadweard Muybridge: Motion studies videodiscs (Master's thesis), Massachusetts Institute of Technology, Retrieved July 01, 2021, from https://dspace.mit.edu/handle/1721.1/70168

Spurr, S. (2007). Chance encounters between body and buildings: New technologies in architecture and dance. *Association of Architecture Schools in Australasia.* https://doi.org/10.5130/aab.al

Stathopoulou, D. (2011). From Dance Movement to Architectural Form (Master's thesis). University of Bath, Retrieved July 01, 2021, from https://researchportal.bath.ac.uk/en/publications/from-dance-movement-to-architectural-form%0Ahttps://purehost.bath.ac.uk/ws/portalfiles/portal/244434/UnivBath_MPhil_2011_D_Stathopoulou.pdf

Tachi, T. (2011). Rigid-foldable thick origami. *Origami 5: Fifth International Meeting of Origami Science, Mathematics, and Education*, 253–263. doi:10.1201/b10971-24

Tachi, T. (2012, Fall). *Lecture 6: Architectural Origami*. Lecture presented at Massachusetts Institute of Technology. Retrieved December 5, 2020, from MIT Open Course Ware: https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-849-geometric-folding-algorithms-linkages-origami-polyhedra-fall-2012/class-and-lecture-videos/lecture-6-architectural-origami/

The 3dsMax-friendly BVH release of CMU's motion capture database, cgspeed. (n.d.). Retrieved May 11, 2021, from: https://sites.google.com/a/cgspeed.com/cgspeed/motion-capture/3dsmax-friendly-release-of-cmu-motion-database

Tsai, L.W. (1999) Robot Analysis: The Mechanics of Serial and Parallel Robots. John Wiley & Sons, New York.

Weber, S. (2008). Ergonomics standards. In *Nursing Management 39*(7), pp. 28-31. https://doi.org/10.1097/01.numa.0000326563.62037.14

Werner, C. D. M. (2013). Transformable and transportable architecture: Analysis of buildings components and strategies for project design (Master's thesis) Catalonia Polytechnic University, Barcelona, Spain.

Yang, J., Abdel-Malek, K. & Blackmore, D. (2006). Swept volumes: Fundation, perspectives, and applications. *International Journal of Shape Modeling, Vol. 12*(1). pp. 87-127. doi:10.1142/S0218654306000858

Zhang, X., Dekel, T., Xue, T., Owens, A., He, Q., Wu, J., Mueller, S., & Freeman, W. T. (2018). MoSculp: Interactive visualization of shape and time. UIST 2018 - Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology, 275–285. https://doi.org/10.1145/3242587.3242592

Zrim, G., et al. (2017). Light distribution in air-supported pneumatic structures: Comparison of experimental and computer calculated daylight factors. *Building and Environment, 119*, 110–127. doi:10.1016/j.buildenv.2017.04.005

APPENDIX

A. Converting Motion Trails into Curves via Python Coding in Maya

The following Python code was written in Maya to convert motion trails into curves.

```
import maya.cmds as mc
#Motion Trail to Curve
sel = mc.ls(sl=True, type='transform')
start = mc.playbackOptions(q=True, min=True)
end = mc.playbackOptions(q=True, max=True)
for each in sel:
    geo = mc.polyCube()[0]
    mc.pointConstraint(each, geo)
    mc.select(geo, r=True)
    snap_node = mc.snapshot(n=each + '_snap', i=1, st=start, et=end, u='animCurve')
    trail_geo = mc.listRelatives(snap_node[0], c=True)
    size = len(trail_geo)
    #Create Curve
    cv_node = mc.curve(d=1, p=[(0, 0, 0), (0, 0, 1)])
    cv = mc.rebuildCurve(cv_node, ch=False, rpo=True, rt=0, end=0, s=size-1, d=1)
    mc.select((cv[0] + '.cv[0:*]'), r=True)
    pts = mc.ls(sl=True, fl=True)
    for i in range(size):
        mc.select(trail_geo[i], r=True)
        cl = mc.cluster()
        mc.rename(cl[1], (each + '_' + str(i) + '_cl'))
    mc.select(cl=True)
    for i in range(size):
        cl_geo = each + '_' + str(i) + '_cl'
        mc.select(pts[i], r=True)
```

```
    cl_pt_node = mc.cluster()
    cl_pt = mc.rename(cl_pt_node[1], (each + '_' + str(i) + '_pt_cl'))
    mc.delete(mc.pointConstraint(cl_geo, cl_pt))
mc.delete(geo, snap_node[0])
mc.delete(cv, ch=True)
mc.rebuildCurve(cv, ch=False, rpo=True, rt=0, end=0, kcp=True, kep=True, d=3)
```