Biological Inspired Joints for Innovative Articulation Concepts

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Summary

Joints are failure points for deployable systems and moving devices. Their reliability is therefore of great concern for space applications. Efficiency is also critical as the power budgets are limited in space and energy dissipation must therefore be avoided. Weight and dimensions must be reduced as much as possible since they have a direct impact on launch costs and thus on space mission budgets. A new type of joint design that meets the extensive and demanding space requirements would be of great use.

This study tries to retrieve interesting mechanisms in the huge pool of clever designs from nature. The number of species of insects is truly awesome, for example there are over 600,000 scientifically described species of beetles with at least twice that number remaining to be discovered and described. And beetles are only one type of insect. To put that number in perspective, there are probably around 10,000 species of birds, and maybe 4,000 species of mammals. The total number of interesting mechanisms in insect species, birds and mammals is almost beyond imagination.

In this work a biomimetic approach is used in order to assess the possibility of improving robotic joints for space applications. The work concerns the identification of classes of joints in nature which could inspire the design of a feasible system in which the mechanical subsystem and the actuation subsystems are merged. This report presents a study with the overall goal of finding biological articulation concepts which, when translated to a mechanical equivalent, can improve performance of articulated robot systems for space applications.

The first part of the study starts with an overview of mechanisms found in nature. In the report 34 mechanisms were identified and described, of which 15 mechanisms on kinematic level, 11 mechanisms on actuating level, and 8 mechanisms on control level. In short it was found that:

1. hydroskeletons have different muscle arrangements that enable different types of motion without a structural skeleton at all,

2. exoskeletons have asymmetric joint activation (sometimes even based on hydraulic principles) with return spring mechanisms,
3. exoskeletons have a closed skeletal structure that flexes on the point where joints are required (so there are no sliding elements),
4. endoskeletons have clever mechanisms that facilitate a.o., energy storage, weight compensation, and muscle translocation, most of them serve dynamic movements,
5. mammals have a highly developed neuro-musculo-skeletal systems that enables optimal and adaptive control.

Combining the findings of the first part of the study brought us an idea for a spring mechanism that can change shape, performing the function of a joint. The principle consists of pre-tensioned springs (agonist-antagonist pairs) of which the agonist is an actuator, and the antagonist is the carrying and enclosing structure (exoskeleton) of the joint. This way a joint without sliding elements can be constructed which reduces energy dissipation, and the need for bearings or lubrication. Using Shape Memory Alloy, SMA, actuators a simple and compact mechanism is proposed.

Biological systems have muscle stretch of 40% whereas NiTi SMA actuators have a typical stretch of 6%. When NiTi SMA wires are applied as muscles the stretch is too small. Therefore Helical shaped SMAs (from Toki Corporation) were used that have a stretch of 100-200%. Since very few is known of these specific actuators, measurements were done. It was shown that the stiffness of these actuators is fairly constant for different loads and temperatures. However, rest length is not constant but depends non-linearly on the load applied. Also there is a fair amount of hysteresis present. This makes modeling and motion control of SMAs difficult.

The joint mechanism requires the exoskeleton structure to have specific mechanical properties that determine the joint stiffness and movement workspace. The degree(s) of freedom that allow motion should be low in stiffness to allow motion. However, a spring force is still required to apply a pre-tension to the SMAs. So there is an optimal stiffness for the exoskeleton structure. The other degrees of freedom should be high in stiffness to make the joint stable for loading in directions other than the controlled ones. To design such a structure is a study on its own. For this study we focused on the joint stiffness and workspace of the degrees of freedom of interest, and the design trade offs that need to be made.

The specs of the joint mechanism depend on the chosen joint geometry and its mechanical properties. Therefore, first a sensitivity analysis with a simple model of the joint mechanism was performed to get some design guidelines for an experimental demonstrator. It showed that there is a design trade-off between workspace and joint stiffness. Theoretically, a workspace of 75 degrees can be achieved, using the optimal exoskeleton structure.

An experimental demonstrator joint was build using 18 components (6 SMA connectors, 3 SMAs, 4 discs, 1 outer spring, 2 screws, 2 bolts). Initially bellows were selected to serve as an exoskeleton. However, these could not be fabricated within the budget. Therefore compression springs were used as outer springs instead. Heating of the SMAs was done by applying a current. With the three SMAs movement in two directions could be realized.

Measurements were done for different settings of the experimental demonstrator and compared to the simulation results. For the given settings, the results of the experimental demonstrator were better than could be predicted with the simulation model. Bending angles of 10 degrees (thus a workspace of 20 degrees) were obtained. However, the theoretical 75 degrees was not realized. The effect of using a stiffer outer spring resulted is a slightly lower workspace, but a larger joint stiffness and stability.

In conclusion, many problems remain still to be solved such as how to design an exoskeleton structure, modeling and optimization of the joint, controllability of the joint, and how to deal with space requirements. All these issues will also depend on a final application. For instance the joint concept proposed is more applicable when the torque requirements are low, but the adaptation to the environment is important (e.g. a spectrometer that needs to be compressed to a rock with a certain force), than for applications where the torque requirements and precision are high (e.g. positioning a robot arm). Nevertheless, by looking at biology we have shown that we can come up with a new articulation concept inspired by nature.

Preface

This report is the midterm report of the study 'Biologically Inspired Joints for Innovative Articulation Concepts'. The study runs within the ESA Ariadna Program, under contract number AO4532-04/6201. Originally it is an extended study of 6 months. However, due to circumstances it was mutually agreed to extend the study towards 12 months, and half the intensity of labor.

The study started on May 17th 2005. The first months were considered as an orientation phase where an overview on biological joint mechanisms was made, found on many different functional levels and in many different types of species. This report presents an overview in a systematical way and presents some candidates for space applications.

This first part of the study will be the basis for inspiration to choose, design and build a biologically inspired joint for space applications in the second part of the study. Although the study is meant to be a paper study, the participants of the research (both from the ESA and the TU Delft side) strongly believe in the added value of building and testing designs. Therefore both parties were committed to realize this goal with the resources already available, and the budget granted by ESA.

The ESA ACT department organized the contract. The description of the work packages was defined during the start up phase of the project. We would like to thank the program officer Dr. Carlo Menon for his constructive input during this phase, and his assistance with writing the first chapter of this report.

Contents

Part I

Review on Biological Mechanisms

Chapter 1

Introduction

The chapter will deal with a brief background of the study. Some space requirements are briefly listed, and the structure of the study is presented.

1.1 Background of the study

The space community has a growing interest in developing high performing joints for spacecrafts, rovers and space mechanisms. In the space field, high performance entails:

- high reliability
- high efficiency
- high compactness
- high lightness

Joints are failure points for deployable systems and moving devices. Their reliability is therefore of great concern for space applications [1] [2] [3]. Efficiency is also critical as the power budgets are limited in space and energy dissipation must therefore be avoided. Weight and dimensions must be reduced as much as possible since they have a direct impact on launch costs and thus on space mission budgets. New typologies of joints are being developed for space applications, especially for slender structures.

Two main categories of systems are of particular interests for space agency programs: joints for deployable structures and joints for robotic applications. Research in the first category is aimed at developing new mechanisms with the following characteristics [4]:

1. "One way" (that is they should deploy only once);

2. Based on energy release, e.g. elastic energy, which was stored beforehand;
3. Passive mechanisms, namely that they are not actuated by mechanical motors.

Research in the second category is aimed at developing new mechanisms with the following characteristics:

1. Actively actuated and controlled;
2. The actuators are embedded on the mechanical joint
3. They are not ”one way”, namely they are continually actuated and their performance should be estimated for a definined life-time.

The research in this report applies to both categories but will focus on the latter category.

One of the main issues that dynamic space structures have to cope with, especially for slender structures, concerns the inertia of mechanical joints with respect to the rest of the structure. An example is given by multi-degree of freedom robotic arms in which the dimensions of the links are mainly chosen for the presence of the joints rather than for the specifications of the payload that must be manipulated by the arm gripper. This issue is of particular relevance for systems with reduced dimensions such as the manipulators which are carried out by scouts and rovers for planetary exploration. One of the most technologically advanced robotic arms of this kind is probably represented by the Instrument Deployment Device (IDD) of the Mars Exploration Rover (MER) of NASA. In this system the inertia of the joint is considerable with respect to those of the robotic links [5][6].

Future space missions will require even stricter constraints on the mass budget of robotic arms. An example is given by the Exomars mission in which the possibility of including an anthropomorphic manipulator will depend entirely on its weight and volume [7] [8]. Therefore a biomimetic approach is investigated in this work in order to assess the possibility of improving robotic joints for space applications [9]. The work concerns the identification of classes of joints in nature which could inspire the design of a feasible system in which the mechanical subsystem and the actuation subsystems are merged.

The number of species of insects is truly awesome, for example there are over 600,000 scientifically described species of beetles. Even more awesome is that there is probably at least twice that number remaining to be discovered and described. And beetles are only one type of insect. To put that number in perspective, there are probably around 10,000 species of birds, and maybe 4,000 species of mammals. The total number of insect species is almost beyond imagination. Obviously there are some interesting mechanisms to be discovered in this huge pool of clever designs.

Biological systems are unique in their capacity to control a wide variety of tasks, ranging from standing, walking, and jumping to fine motor tasks such as grasping and manipulating. It is likely that a Central Nervous System (human, animal, insect, o.a.) takes advantage of the (non-linear) dynamic features of the system.

1.2 Goal of the study

This report presents a study with the overall goal of finding biological articulation concepts which, when translated to a mechanical equivalent, can improve performance of articulated robot systems for space applications.

1.3 Space requirements

In space specific requirements need to be fulfilled due to the harsh conditions in which systems need to operate. The environment constraints however depend on the specific mission for which the system is designed. Environment characteristics of the free space, for example, are very different form those of planets or even more different of those of comets. All space mechanisms must however be designed for mission phases which are common to all space missions as the launch and the cruise phases. Constraints, which were considered in order to explore a new joint concept design, were therefore those which are common to the main structural space systems. A complete list of requirements would probably still take thousands of pages, and would be devastating for new innovative ideas, like being generated under the ESA Ariadna program. Therefore a minimal list of space requirements has been composed by L. Scolamiero (11/4/05), that serves as a guideline rather than a strict list of conditions that need to be met:

Functional requirements (rotary joint):

- Workspace: 90-180 deg.
- 1 or 2 DOF hemisphere workspace
- No backlash (< 0.001 deg.)
- Payload 1-3 kg (at COG = 1-2 meters)

- Life < 100.000 cycles
- Speeds typical < 1 deg/s
- 50 - 100 Hz first eigenfrequency (locked situation)
- static joint stiffness 10e4 to 10e6 N/m

Environmental requirements:

- 25 - 50 g quasi static (at launch)
- 30 g RMS vibration
- temperature -40 °C to +80 °C
- temperature fluctuations between low and high
- low outgassing!

General requirements/consideration

- Reliability (=simplicity)
- Friction can increase due to environmental conditions (safety factor 6)
- Preload during launch/ no preload during operation

1.4 Structure of the study

Part I presents an overview of mechanisms found in nature whereof the joint layout and the kinematics are discussed in Chapter 2, the joint activation and behavior in Chapter 3 and the joint control in Chapter 4. Chapter 5 will discuss the mechanisms related to the space requirements set in Chapter 1. Part II presents a new robotic design inspired by mechanisms found in Part I. In Chapter 6 a joint design is proposed. In Chapter 7 tests and measurements on the actuator material are described to give insight in the properties and characteristics of the material and its feasibility in space. Chapter 8 will evaluate the design by means of modeling and optimization. Chapter 9 shows the results from testing with a prototype and finally Chapter 10 gives an overall conclusion of the design and some recommendations for future research.

Chapter 2

Joint lay out and kinematics

In nature there are three skeletal types, which make a first differentiation between articulation types [10]:

1. Hydrostatic skeletons
2. Exoskeleton skeletons
3. Endoskeletal skeletons

Joints are defined as a body moving with respect to another. The bodies do not necessarily need to have a rigid inner or outer framework. In that case the joint will most likely be a hydrostatic joint, and moves by changing form. Exoskeletons have a rigid external framework that kinematically defines the way a joint moves, whereas endoskeletons have a rigid inner framework. All three have different lay outs and kinematics that will be discussed.

2.1 Hydrostatic joints

A variety of animals (like worms, octopi, jelly fish,...) make all their movements with a hydroskeleton. Also, many animals move some of their body parts using a hydroskeleton (like the elephant trunk, the penis, intestines, tongue, ...). Although the functionality might differ a lot, there is only a limited number of hydrostatic mechanisms known in biology. There are two basic classes of hydrostatic skeletons: open and closed structures. The closed versions remain their volume during movement, whereas the open versions receive fluid from somewhere else, e.g. the squid that takes up and expels seawater to create a jet propulsion mechanism.

It is difficult to isolate the joint in the hydrostatic skeleton, since the mechanism is a deformable, often jelly like, substance that simply changes form. There are neither fixed hinges nor structures that can resist compression. So how is movement produced? Basically, the arrangement of muscles and structure determines the way the hydroskeleton is deformed, and consequently which movement is generated. There are some simplifying features in the arrangement of muscles and the consequent movements (see Figure 2.1). Parallel muscle arrangements can only exert pulling forces while the circular muscle arrangements transfer pulling forces into pressure forces in order to lengthen and strengthen the segment.

Muscles parallel (see Figure 2.1(B)) to the long axis (longitudinal muscles) and uniformly distributed along the cross section of the hydroskeleton produce shortening. A unilateral contraction of longitudinal muscles produces a bend in the hydroskeleton. This principle has been used to activate artificial fingers [12].

Muscles perpendicular (see Figure 2.1(C))to the long axis of a hydroskeleton are always antagonistic to longitudinal muscles. They lengthen the hydroskeleton by squeezing it. A circular (or circumferential) arrangement combined with a longitudinal arrangement keeps the inner part of the hydroskeleton free of muscles, like in abdomen or in worms (see Figure 2.2).

Another perpendicular arrangements is transverse, which can flatten the hydroskeleton. Leaches use this principle to increase their body area to swim. A final perpendicular arrangement is radial, used in the elephant trunk. This compact muscle arrangement provides a high power density solution.

The final class of muscle arrangements is oblique to the long axis of a hydroskeleton (See Figure 2.1D). It produces torque along the longitudinal axis. Contracting two agonistic muscles at the same time produces shortening. This type of mechanism is used in artificial McKibben muscles, in which the transverse displacement at increased pressure is converted into shortening through the passive diagonal bands.

2.2 Exoskeleton joints

All arthropods (Like arachnids (spiders), crustaceans (crabs), scorpions, and insects) have an external, cuticular skeleton provided with softer parts which form flexible (deformable) joints. While it is hard and protective externally, the cuticle must still accommodate the arthropods sense organs e.g. hairs and eyes, and provide a solution in areas where elongation of the outer surface is required (Figure 2.3). The external cuticle is therefore hardest on the head and thorax and limbs, apart from the softer cuticle that forms the flexible joints of the limbs and mouthparts.

Spiders move their legs by varying their blood pressure pumping blood in and out each leg. The seven segments of a spider's leg (see Figure 2.4)

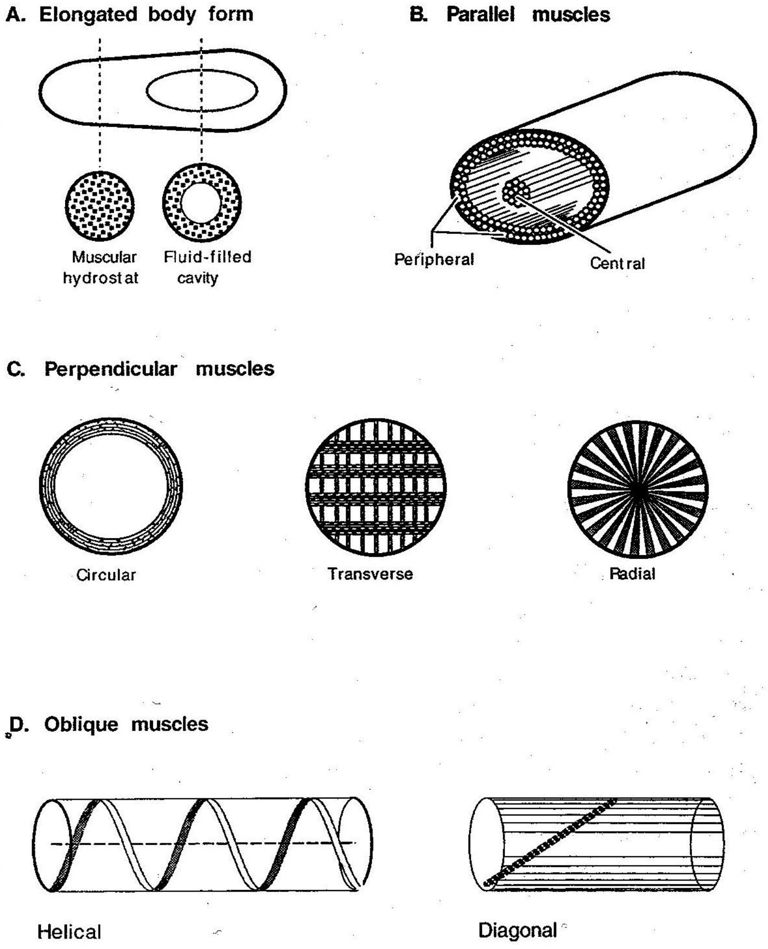

Figure 2.1: Types of muscle arrangements found in elongated constant-volume hydroskeletons. (A) The general form of such hydro-skeletons is either muscular hydrostat (left), in which muscle and other tissues form a solid structure,or muscles in the body wall surround a fluid-filled cavity (right). The muscles in either type of hydroskeleton are classified by their arrangement relative to the long axis: parallel (B), perpendicular (C), or oblique (D). Some typical subtypes of each of the arrangements are shown: (B) Parallel muscles are often in bands located either centrally or peripherally. (C) Perpendicular muscles may form circular bands around the structure, or transverse or radial bands through the structure. (D) Oblique muscles may form helical bands or diagonal bands. [11]

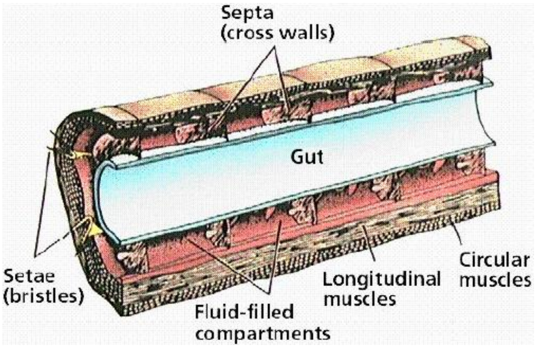

Figure 2.2: Hydrostatic skeleton of a worm. A circular arrangement of muscles combined with a longitudinal arrangement keeps the inner part of the hydroskeleton free of muscles. Adapted from [13]

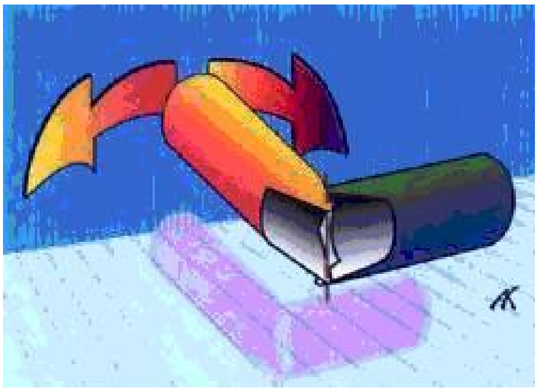

Figure 2.3: Cuticular skeleton: a hard, protective skeleton with softer parts that form flexible joints [14].

make them much more flexible than human legs, which only have two segments. Like humans, spiders have muscles that bend the legs closer to the body. However, spiders do not have muscles that move the legs away from the body. Together, cuticle and blood make up a pressurized unit, similar to a hydraulic system . Each time a spider needs to stretch a leg back out, it must pump fluid into that leg. Then, to bend the leg back, pressure is relaxed and the fluid flows out of the leg as the muscles do their work. This is similar to the way a garden hose gets stiff and moves around when filled with water, and then gets limp again when the water drains out. [15] This explains why injured or dead spiders always have their legs bent inwards - they can no longer control their blood pressure and this allows the strong flexion muscles to dominate and pull the legs in under the body.

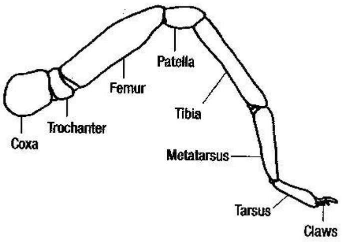

Figure 2.4: A spider paw is moved by varying the blood pressure by pumping blood in and out each leg.

Figure 2.5: Muscles in exoskeleton In Arthropoda, muscles are surrounded and protected by the exo-skeleton. As joints have only one axis, there are only two components of the joint motion. Therefore two muscles are sufficient: agonists and antagonists [14].

Crabs activate their joints directly with muscles, without the use of pressuring fluid. This implies that the muscles must be arranged inside the enclosure (see Figure 2.5). In the picture it can be seen that a real danger exists for muscles to pass the joint axis and become a flexing muscle instead of an extensor. If this occurs, the leg will not be able to bend back again by itself. Crab limbs therefore have a very limited range of motion.

Arthropods need to molt once in a while in order to grow. In the first period of molting the exoskeleton is very soft until is hardens. What is amazing is that during this period the arthropods are able to transmit the forces required to move, although the skeleton cannot withstand these forces. Apparently the arthropods do not fully rely on their exoskeletons as a pressure force transmitting linkage of elements, but also as a closed hydrostatic structure. The technique of switching between these two techniques is not yet understood.

2.3 Endoskeleton joints

Unlike the exoskeletons the endoskeletons show a wide variety of joint types. The ransom to be paid is the complexity of structures and function, and the fragility facing trauma and external aggressions.

Besides the immovable joints (synarthroses), like the sutures in the human skull and the slightly movable joints (amphiarthroses), like the cartilage attachments of the ribs and the vertebrae discs, there are free movable joints (diarthroses) which are the most interesting. There are seven types of free movable joints found in the human body, illustrated in Figure 2.6:

- Ball-and socket (e.g. the hip joint and gleno humeral joint)
- Ellipsoidal (e.g. fingers)
- Condyloid (e.g. knee joint)
- Saddle (e.g. part of the wrist joint)
- Pivot (e.g. radius/ulna joint)
- Hinge (e.g. elbow joint)
- Plane/gliding (e.g. scapula joint)

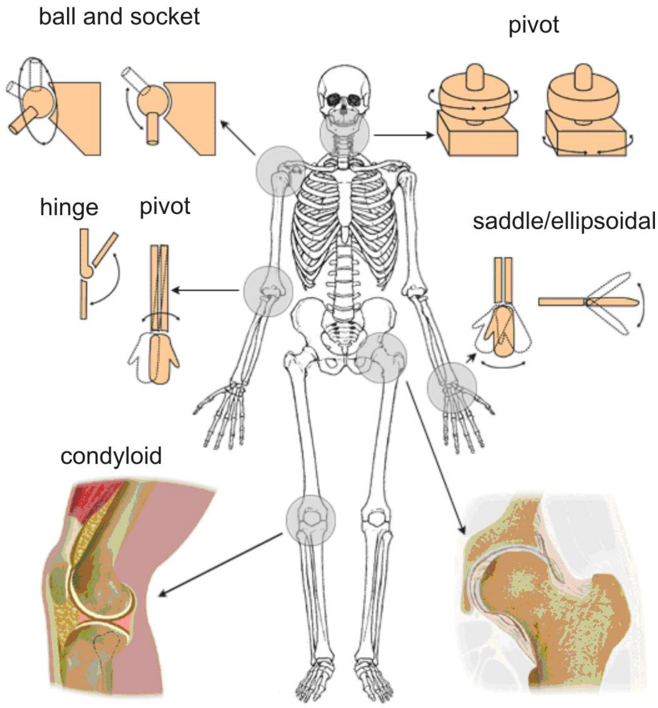

Figure 2.6: Joint types found in the human skeleton. Adapted from [16]

The joint surfaces conduct pressure while the ligaments exert pull forces to stabilize a joint. The number of degrees of freedom is determined by the

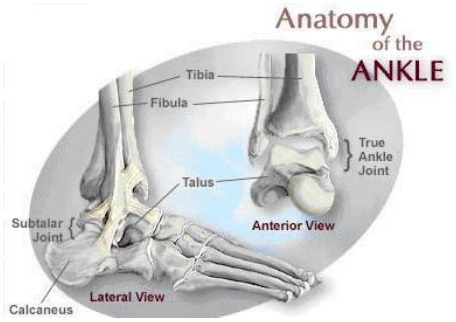

Figure 2.7: Multi-axis joint of the human ankle [18].

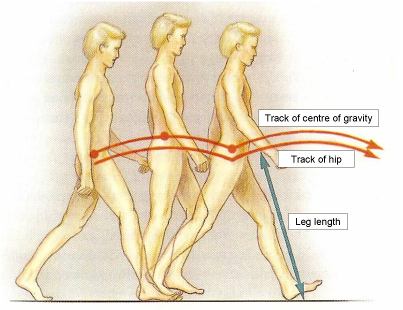

Figure 2.8: The foot is a cluster of multiple bone segments and ligaments that might let the foot work as a wheel [17] [14].

shape and the position of the joint surfaces and the number of ligaments that are stressed. Furthermore can the contact points in di-arthrodial joints and/or multiple stressed ligaments restrict the motion and the degrees of freedom which is for instance the case for the knee joint.

It must be mentioned that joints often have a more complex mechanical behavior than assumed at first glace. For instance the shoulder joint can be considered as a ball and socket joint, but its center of rotation shifts during movement. Another example is the ankle joint. In many biomechanical studies the human ankle is assumed to be a simple hinge joint, and the foot is assumed to be rigid. In reality the ankle mechanism is working as a multi-axis joint (see Figure 2.7), and the foot is a cluster of multiple bone segments and ligaments. Because the foot deforms, the joint axis translates which results according to some researches in a wheel-like motion (Figure 2.8) [17] [14].

In Chapter 3 we will also see a special energy storage function of the foot. Besides providing a range of motion, joints will also restrict the motion to a certain range. This can and will be used to prevent the muscles from overstretching. This is depicted in Figure 2.9 for the elbow joint. Also for other joints end stops by bone structures are possible, but scarcely used. For instance for ball and socket joints the ”embedding coupling index” is never higher than 50% (illustrated in Figure 2.10). (The Coupling Index indicates the strength of coupling between components in a product [14]).

Low friction movement

In joints of endoskeletons the bones perform a rolling and sliding motion with respect to each other. Amongst other functions, the complex joint lay out prevents high friction forces.

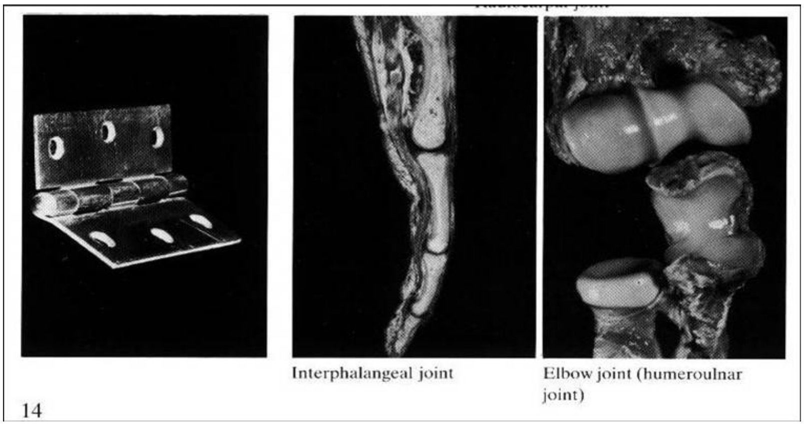

Figure 2.9: Elbow joint restriction to prevent muscles from overstretching [19].

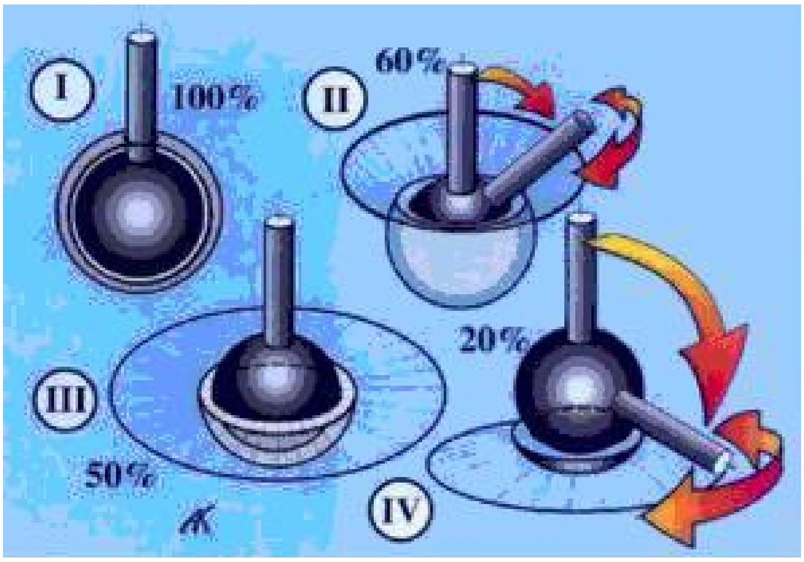

Figure 2.10: Coaptation and interlocking coupling Index None of the biological articulations includes an ”embedding coupling index” higher than 50%. In the dry skeleton, no articulation would stay interlocked. (I) A 100% ”Embedding Index” (E.I.) offers a maximum stability, but no motion at all. (II) With a 60% Embedding Index. the stability is absolute but movements are very limited. (III) A good mobility is provided by a 50% E.I., as in the hip, but a dislocation is possible. (IV) In the shoulder, a 20% E.I. gives a large mobility but a poor stability. [14].

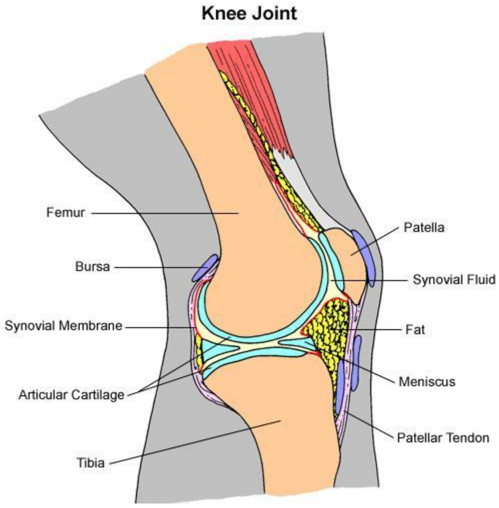

Figure 2.11: The knee joint has very low friction due to cartilage and synovial fluid that acts as lubrication [16]

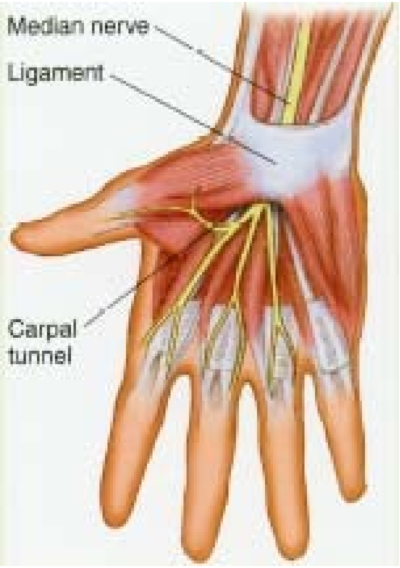

Figure 2.12: By means of tendon tunnels, tendons do not take the shortest route between the points of attachment in the human wrist [20]

The bones are capped with shock-absorbing cartilage. This is a tough, smooth, slippery material that allows bones to glide over each other easily. This gives a coefficient of friction of < 0.002. The cartilage is assisted in its friction-reducing role by the synovial fluid in the joint (Figure 2.11). This clear fluid has the same role as lubricating oil in a machine to allow repeated movements of the joint, but also for the articulated limbs to bear someone's weight without any resulting damage. The synovial membrane secretes and constricts the synovial fluid into the joint cavity, possibly supported by a sac of fluid, called a bursa. Ligaments and joint capsule are a tough, fibrous material that attaches to bone on either side of the joint. Ligaments help by contributing to joint alignment and stability.

Muscles transmit forces over several joints. When the body segments are bent, the tendons tend to move to the shortest route between the points of attachments. However, the tendons should remain within the contours of the body during the movement. Tendon tunnels, which have very low friction characteristics, guide the tendons as if they were pulleys, for instance in the human wrist (Figure 2.12).

Chapter 3

Joint actuation and behavior

In biological systems actuation is realized with muscles. The way in which a muscle generates force and the characteristics of the muscles are explained in this chapter. Special joint features and behavior, which was not dealt with in the previous chapters like elastic mechanisms, multi-DOF solutions, friction reduction schemes, and special reflexes are discussed as well.

3.1 Muscles

Muscles are linear actuators, where force is multiplied by the moment arm to exert moments around the joints. Muscles can only exert tension forces, therefore pairs of muscles (called agonist and antagonist) are required to exert moments in both directions around a joint. If both agonist and antagonist muscles are contracting, the resulting moment is the summation of positive and negative moments. In this situation, the joint stiffness will increase. The system with two actuators around a joint allows for control of joint moment and joint stiffness, which is important for stability and control.

Muscles have a function for information transfer and for energy transfer. On the one hand, muscles convert neural input from the brain into mechanical output, enabling animals to exert forces on their environment. On the other hand, chemical energy available in the body is transformed into mechanical energy, useful for generating motions but also for generating heat in case of warm-blooded animals.

Muscles exert force when activated by stimuli from a nerve or artificially by an electrode (Functional Electrical Stimulation, FES). These stimuli start a chain reaction of chemical processes that initiate a connection between a actin filament and opposite myosin filament (See Figure 3.1). Such a connection is addressed as a cross-bridge. The smallest functional component is the single actin-myosin interaction; nonetheless, those build up the sarcomeres, as smallest functional units, delimited by the so-called z-lines. In a muscle fiber a large number of sarcomeres are arranged in series and in parallel as well. The alignment of sarcomeres and the many alternating light and dark bands of the sarcoplasm attribute to the name striated muscle. Movement is initiated when the myo-filaments slide past one another driven by cross-bridges which attach and detach at the myofilaments exterting forces like in a rowing boat. A large number of muscle fibers arranged in parallel form a muscle belly [21].

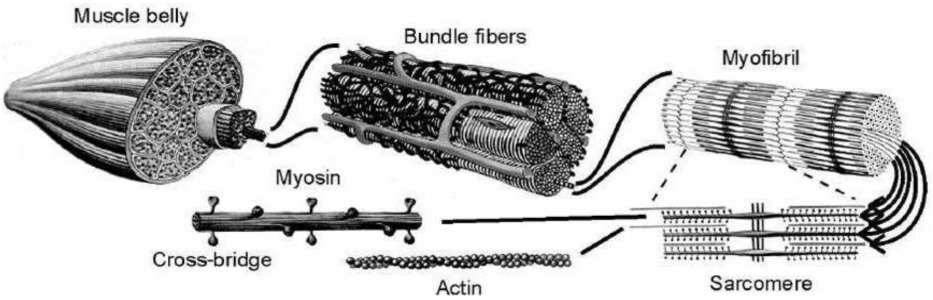

Figure 3.1: Muscle anatomy. Adapted from [21]

An aponeurosis is a tendinous structure inside the muscle belly. Through aponeuroses (tendon-sheets) and tendons, the muscle fibers are attached to the bone structure at origin and insertion. An aponeurosis is made of tendinous tissue at which fibers are attached at an angle. At one end an aponeurosis turns into a tendon. The arrangement of the fibers with respect to the line of pull in muscle defines muscle architecture. A schematic representation of a classification in architectural characteristics is given in Figure 3.2. The most common muscle architectures are the parallel fibered and the pennate muscles. In parallel fibered muscle, fibers are arranged along the line of pull of the muscle. In pennate muscle fibers are relatively short compared to the muscle length and have an angle of operation with respect to the muscle line of pull. That so many different muscle architectures exist suggests a relation with the function of the muscle. It can be shown that a pennate muscle, with the same fiber length and volume as a parallel fibered muscle, can exert a larger force at the cost of a smaller contraction velocity.

Nonlinear behavior of muscles

Numerous models are developed to describe aspects of muscle functioning, with the purpose to describe or predict how muscle behaves under certain conditions, such as the force-length and force-velocity characteristics. There are basically two different models developed: a Hill-type model that describes muscle function on a macroscopic level, based on empirical relations;

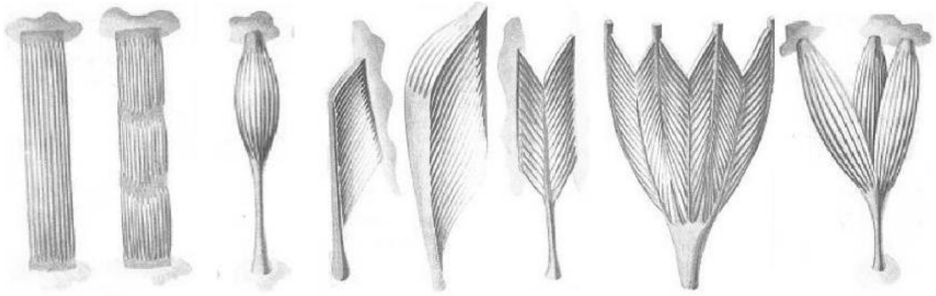

Figure 3.2: Variety of muscle architectures. Adapted from [21]

and a cross-bridge model that explains muscle behavior on a microscopic level. Without going into the concepts of these models, Figure 3.3 and Figure 3.4 give the force-length and force-velocity characteristics that are extracted from these models. The actual shape of the force-velocity relation is defined by a number of muscle-dependent parameters. It is known that the force output is contraction history dependent [22] and effects like fatigue are not considered. From the diagrams it is obvious that the mechanical power output has an optimal value between zero and maximal velocity. At zero velocity (isometric contraction) the mechanical power output is zero. This does not mean that no chemical energy is required, as can easily be verified by carrying a weight.

The descending limb of the force-length relation can show a negative slope. In a numerical model this relates to a negative stiffness, which may become numerically unstable. In real life this negative stiffness is unlikely to occur. One should keep in mind that the force-length relation is the result of a large number of isometric experiments. For the purpose of modeling these separate points are fitted with a curve.

3.2 Elastic mechanisms

In biological systems all kinds of elastic energy storage occur [23]. This energy storage takes place in tissues such as: tendon material (e.g. Achilles tendon, foot arch), Ligamentum nuchae (spinal ligaments of hoofed animals), Mesogloea (collagen fibres in anemones and jellyfish), and muscle fibres (for small length changes). These elastic mechanisms are used for different types of mechanisms.

A simple mechanism for which a spring can be used is as a return spring. Since muscle can only exert tension forces, an agonist-antagonists construction is required. However, when one of these muscles cannot be placed, a

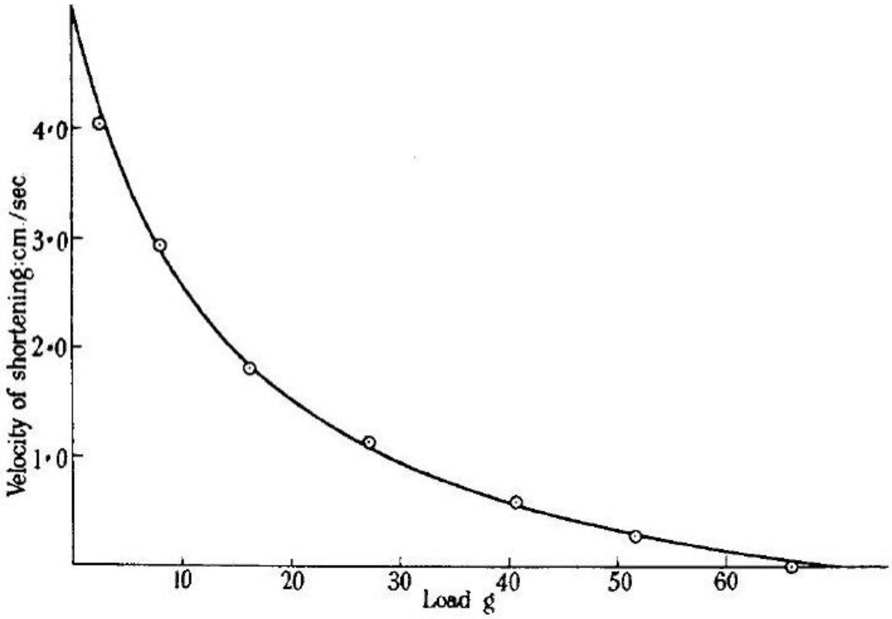

Figure 3.3: Force-velocity curve: Experimental data from Hill (1938).

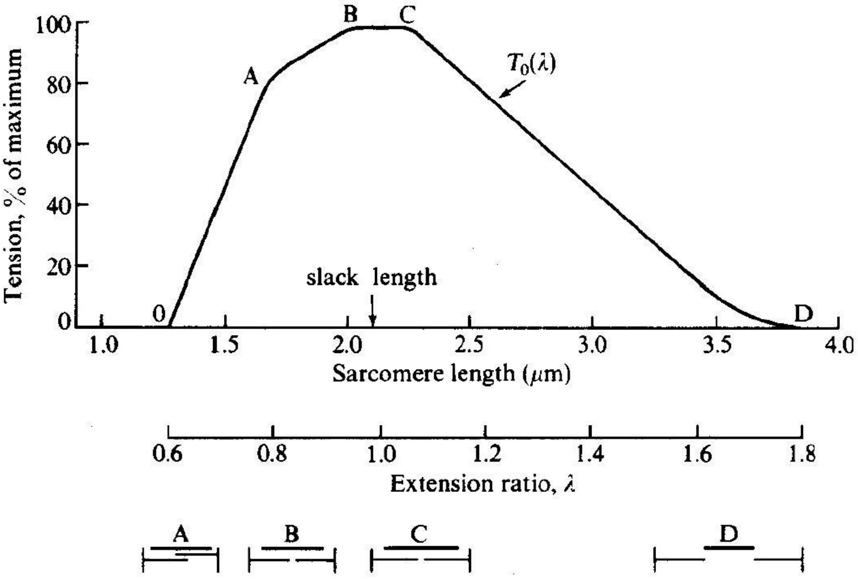

Figure 3.4: The (isometric) force-length curve for frog skeletal muscle fibers. The relative positions of the actin and myosin filaments for A to D are shown at the bottom. From Gordon et al. (1966).

return spring can provide a solution. This is the case for scallops (see Figure 3.5), because of their exoskeleton type of construction. The hinge ligaments provide a spring-like opening torque. A disadvantage of this mechanism is that the closing actuator must exert a closing force continuously to counteract the spring.

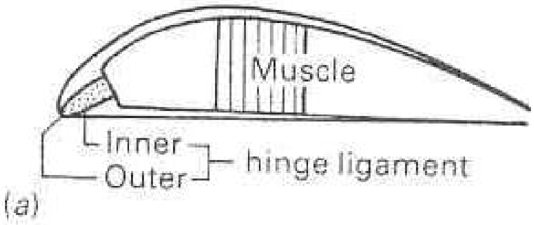

Figure 3.5: Diagrammatic section through a scallop (Pecten) showing the hinge ligaments and adductor muscle. Adopted from [23]

A more advanced mechanism for a spring is a (quasi-) static weight compensation. Here the spring characteristics are defined such that the change in potential energy due to gravitational energy change is exactly counter balanced by the change in potential energy due to elastic energy storage. In other words: the gravitational energy is stored in spring energy and vice versa. A simple version of this mechanism is shown in the neck of hoofed animals like deer, camel and sheep (see Figure 3.6). In the feeding position fairly little (in the ideal case no) tension is required in the neck muscles. Mechanical mechanisms have been made which operate in a similar way over a complete range of motion [24].

Springs can also be used for dynamic tasks, like oscillations. For instance in running, the leg can act as a simple bouncing stick. The kinetic and gravitational energy are stored in the spring during landing and released during lift off. This bouncing effect can be energetically very efficient. This mechanism is found in the legs of Humans, Walibi (kangaroos), and hoofed animals. Proof has been found by measuring metabolic energy uptake during running, and by stretch measurements of the tendon material. Also running robots have been made using this principle [25]. The big advantage of this mechanism is that it reduces the amount of work that needs to be performed by the muscles (or actuators). In legs the main energy storage takes place in the foot arch and the Achilles tendon (see Figure 3.7). However, it is also suggested that during galloping motions hoofed animals also use the spine as a bending spring to store substantial amounts of energy.

Another complex and demanding dynamic task is flying. Like walking it

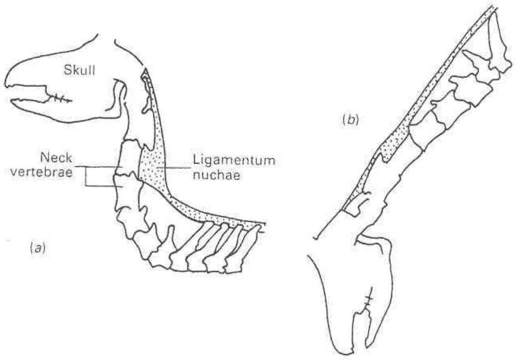

Figure 3.6: Outlines traced from X-ray pictures of a roe deer (Capreolus capreolus) carcase with the head in the alert position and lowered for feeding. The position of the ligamentum nuchae is indicated by stipple. Adopted from [23]

is also a periodic movement, and thus it could benefit from spring solutions. One of the mechanisms found in Sarcophaga (flesh flies) is the click mechanism. It works as a bi-stable spring mechanism (see Figure 3.8). Although the presence of this bi-stable mechanism is argued, it is believed that this mechanism is used to flatten the wing speed profile in the middle of the stroke.

Another fly mechanism is the indirect actuator principle. A double-hinged attachment of the wings to the thorax, one hinge being connected to the side of the thorax and the other to the tergum, indicated in Figure 3.9. The dorsoventral muscles, running from the tergum to the bottom of the thorax, contract to raise the wings. The longitudinal muscles, running along the length of the thorax, contract to lower the wings. When the dorsoventral muscles contract, the tergum is lowered and the wings rotate about the outer hinges and rise. When the longitudinal muscles contract, the tergum is forced upward again, and the wings rotate in the opposite sense about the outer hinges. The housefly for example and other Diptera, employ this musculature. The benefit of the indirect muscle system is that it allows much more rapid beating.

Another task where springs can be useful is jumping. Storing energy gradually in a spring and instantly releasing it creates a catapult like effect. This effect is used for instance by grasshoppers [23]. A small flexor muscle counteracts a huge extensor muscle. Because the moment arm around the rotational point of the 'knee-joint' is big, the leg does not stretch. Force builds up gradually until the flexor muscle relaxes. All energy stored in the extensor muscle and the surrounding elastic material is released. The

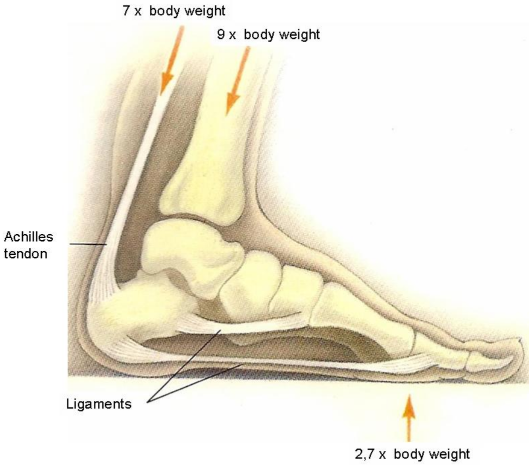

Figure 3.7: Achilles tendon is used for energy storage during repetitive motions like for instance walking [17].

mechanism is shown in Figure 3.10.

3.3 Multi-DOF solutions

In some joints the muscles are located remote, e.g. the fingers of the human hand (see Figure 3.11). When the muscle crosses multiple joints, it is called a polyarticular muscle. When the forces are transmitted from the muscles to the segments that need to be moved, a torque is exerted on all degrees of freedom that the tendon crosses.

Polyarticular muscles can distribute the work they perform over several degrees of freedom. The main advantage is that the mass of the muscles is kept proximally, which reduces the moment of inertia of the limb. In the legs, two bi-articular muscles are acting in diagonal: rectus femoris and gastrocnemius. The hip extension favors the efficiency of the rectus femoris as extensor of the knee. On the other hand, the knee extension enhances the action of the gastrocnemius as extensor of the ankle (so called plantar flexion). So, when the gluteus magnus (booty muscles) is contracting, a part of its power is transferred to the ankle extension through the rectus femoris and gastrocnemius (Figure 3.12).

In camels, the principle of polyarticular muscles and tendons is so far developed that only the hip muscle moves the complete leg as a mechanism. The advantage is that less muscles are required than degrees of freedom. This underactuated system consumes less energy.

Another function of polyarticular ligaments are to restrict the motion to

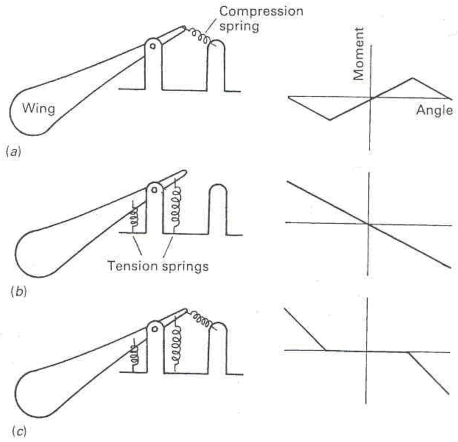

Figure 3.8: Diagrams of possible wing mechanisms: (a) a click mechanism; (b) a mechanism with springs representing wing muscles; (c) a system with both a click mechanism and muscle springs. The graph shows the moments that the springs exert on the wings at different wing angles. [23]

a certain workspace. This will keep muscles in the length range where they can exert forces. An example is the hip joint, depicted in Figure 3.13.

Another advantage of poly-articular muscles is that they can dissipate energy at one joint (braking the joint velocity) and 'transfer' the energy to the next joint in which the velocity is increased. This will result in a whip-like mechanism, which can be found in pitching a ball, and in the take-off during jumping.

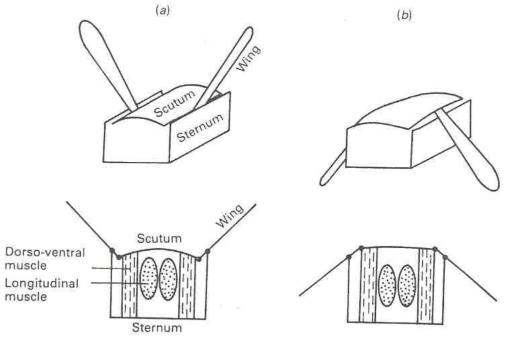

Figure 3.9: Diagrams showing how the indirect wing muscles of dipteran flies move the wings. The lower diagrams are transverse sections. [23]

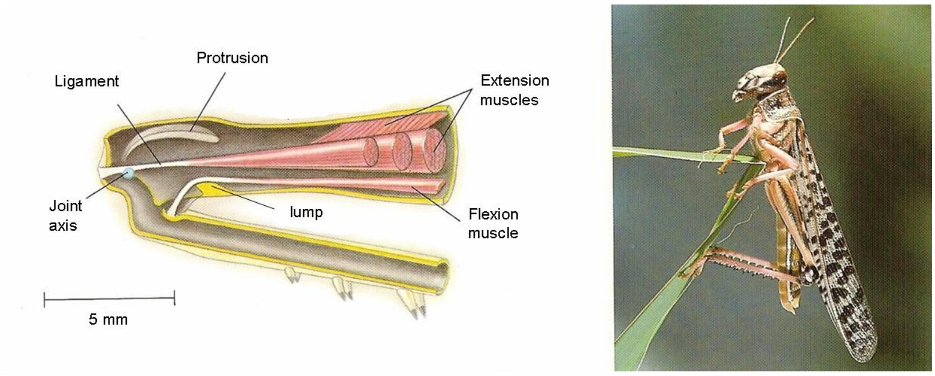

Figure 3.10: Storing energy in a spring and instantly releasing it creates a catapult like effect. Grasshoppers use that mechanism to jump. The lump shown provides a large moment arm for the flexor muscle to counteract the huge extensor muscle [17].

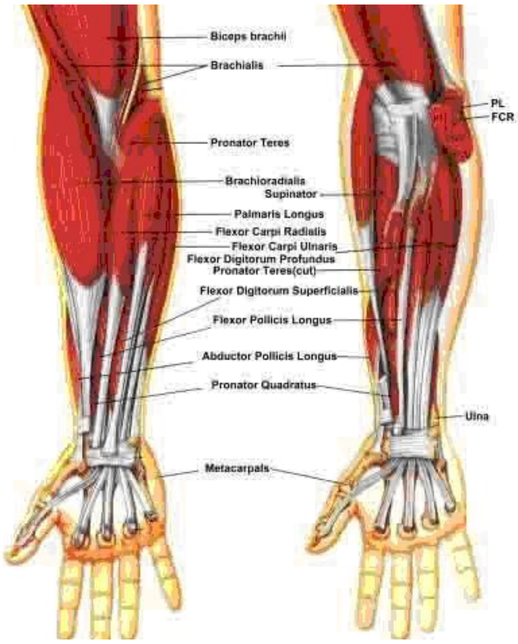

Figure 3.11: The muscles in the arm are used to move the fingers as well. The muscles crosses multiple joints and are called polyarticular muscles [**?**].

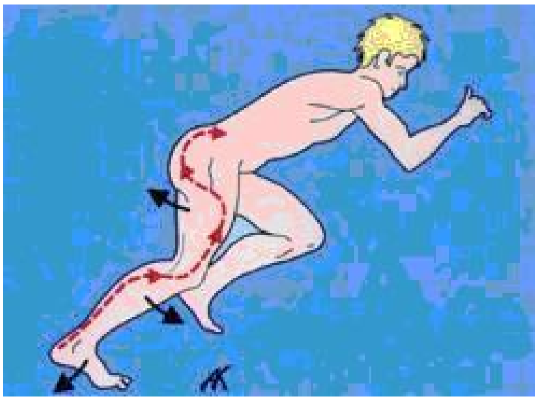

Figure 3.12: The poly-articular diagonal chain of the lower limb. In the lower limb, there are two bi-articular muscles acting in diagonal: rectus femoris and gastrocnemius. The hip extension favors the efficiency of the rectus femoris as extensor of the knee. On the other hand, the knee extension enhances the action of the gastrocnemius as extensor of the ankle (so called plantar flexion). So, when the gluteus magnus is contracting, a part of its power is transferred to the ankle extension through the way of the diagonal system of the two bi-articular muscles. [14].

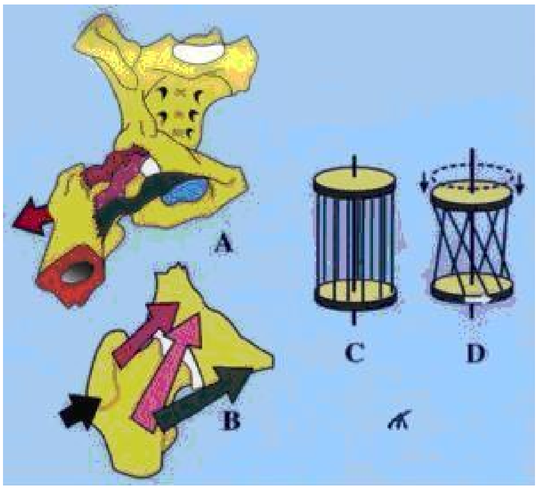

Figure 3.13: The hip blocking in complete extension. The three ligaments of the hip's anterior aspect have an oblique trajectory, winding around the femoral neck. Consequently, they are loose in flexion (A), and tight in extension (B). Thanks to a model made with two circular plates with threads tightened between them (C): when a plate is rotating (D), the threads are tighter and the plates are approximating one to another [14].

Chapter 4

Joint control

The chapter discusses how joints are actuated and controlled. First a brief description is given of the neuro muscular system, next the control is discussed in two parts: feedback & reflexes and feedforward & learning. Finally the non-linearities and some special reflexes are discussed in a separate section.

Systems and control is necessary for mechanical problems within muscle-skeleton system. Since muscles have nonlinear behavior, the control is complex. This chapter translates the neuromuscular system in a technical way so that for controlling biological inspired articulation, possible control methods can be extracted.

4.1 Neuro muscular muscle systems

In Figure 4.1 a block scheme of a neuormuscular system is shown, with the Central Nervous System as controller, the muscle as actuator, the body segments as plant and the sensors (muscle, visual, vestibular, skin). The neuromuscular system is a distributed control system. Properties of the actuator, sensor and plant help to control the system. In contrast, in technical systems often the controller has to compensate for the undesired actuator properties. Muscles have intrinsic non-linear properties, in that they have a non-linear force-length relation and non-linear force-velocity relation (see Figure 3.3 and Figure 3.4). Muscles have an intrinsic stiffness and viscosity. In comparison, electric actuators have no intrinsic stiffness (stiffness is the result of a position feedback loop); hydraulic actuators have a very high intrinsic stiffness, which should be reduced by the control algorithm.

The joints in between the body segments have often more than one DOF, e.g. like the rotational joint. Muscles often span more than one DOF, and

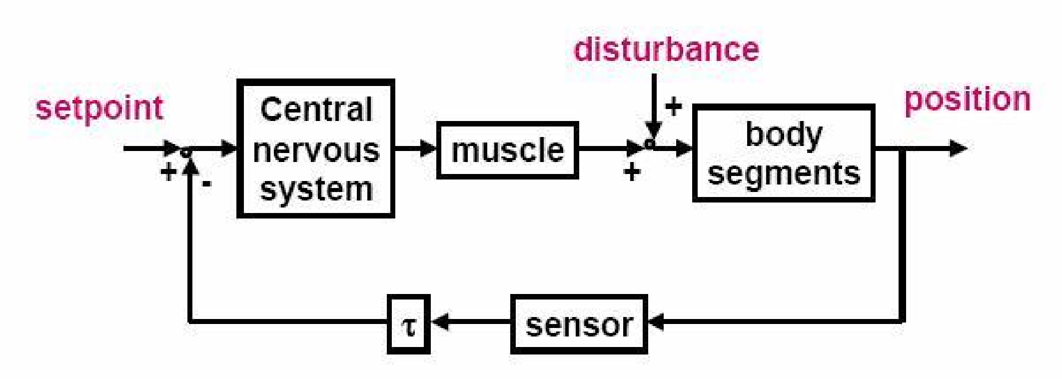

Figure 4.1: Conceptual scheme of the motion control of a musculoskeletal system, with a linkage system (body segments), actuators (muscles), sensors (proprioceptive and tactile sensors, visual and vestibulary system) and the controller (Central Nervous System). τ represents the time-delays caused by transport and processing in the nervous system.

the actions of these muscles are therefore coupled to each other. Since the muscles are linear actuators, their moment arm can change during rotation. This will most often lead to a lower joint stiffness, since the moment arm will increase in the direction of the motion, and decrease opposite of the motion. One exception is the neck, where the bony extensions (processus spinosus) help the geometrical joint stiffness, because the moment arms will actually increase in the direction of the motion.

There is a redundant number of sensors in the human body. Muscle spindles record muscle length and contraction velocity, Golgi Tendon organs (GTO) record muscle force, the visual system provides information about position and velocity, the vestibulary system records angular and linear acceleration and the skin sensors provide force information for small forces exerted on the skin.

4.1.1 Golgi Tendon Organs

The Golgi tendon organs (GTO) are located in the muscle tendons. About 50 GTOs are located in a major tendon. The GTOs consist of nerve endings that are intertwingled with the collagen fibers of the tendon (Figure 4.2).

When the tendon is stretched, the nerve endings are 'squeezed'. The denervation of these nerve endings results in a spike train along the afferent nerve to the CNS. This afferent nerve is called the Ib afferent nerve fiber. The deformation of the tendon is in accordance with the muscle force exerted

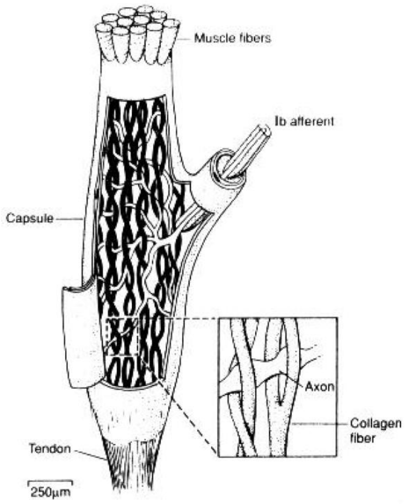

Figure 4.2: The Golgi tendon organ consists of a nerve ending intertwingled with the tendon fibers. The Golgi tendon organ is sensitive to the muscle force exerted through the tendon.[26]

along the tendon. Therefore, the Golgi tendon organs provide information about the muscle force.

In the earlier days, experiments in which the whole muscle was stretched resulted in little activity of the GTO. Therefore, it was thought that the function of the GTO was not in the fine motor control, but merely to detect large forces in the tendons and protect the tendon against damage. This theory was also in accordance with the fact that the GTO are connected to the -motor neuron through an inhibitory interneuron, i.e. when the tendon was stretched, the GTO caused the α-motor neuron to cease firing. However, this theory has been abandoned for two reasons. In the first place, if the α-motor neurons cease firing while the large external force is still stretching the muscle, the muscle will be stretched rapidly, and presumably the muscle fibers will be damaged. Secondly, more recent experiments showed that the Golgi tendon organs are especially sensitive to the forces exerted by the active muscle fibers, more than to the passive forces transmitted though endomysium and perimysium (the connective tissue around the muscle fibers).

The GTO is a sensor inside a force feedback loop, in which the muscle force is fed back to the CNS. Forces down to a few N can be sensed by the GTO. In addition, the Ib afferent fibers are among the fastest transmitting sensory fibers in the peripheral nervous system. It will be shown in the

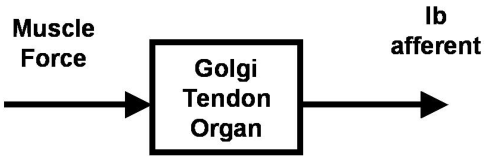

Figure 4.3: Block scheme of a Golgi tendon organ. The only input is muscle force, and the Ib afferent nerve signal is output which has a static and linear relation with the muscle force.

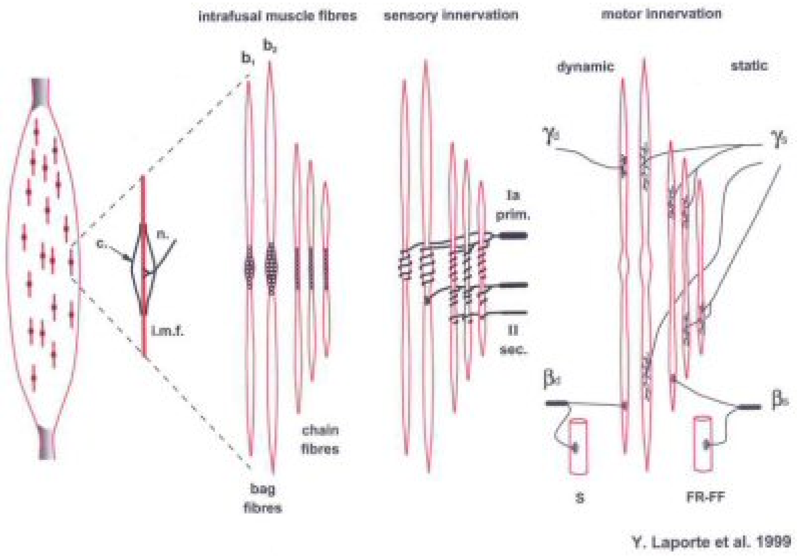

Figure 4.4: A muscle spindle unit consists of 3-5 nuclear chain fibers and 1-2 nuclear bag fibers.[27]

next section that the force feedback loop is an important inner loop of the velocity and position feedback loops. Inside the GTO, there are no dynamic effects, i.e. the Ib afferent nerve output is always proportional to the muscle force. Hence, there is a static (no time-history) and linear relation between the muscle force and the afferent nerve (see Figure 4.3).

4.1.2 muscle spindles

In contrast to the Golgi tendon organs, muscle spindles are very complex sensory units. A muscle spindle is a unit consisting of about 3-5 nuclear chain fibers, and 1-2 nuclear bag fibers (Figure 4.4). A muscle spindle has a length of about 8 mm and is located parallel to the muscle fibers. The muscle spindle endings are attached to the muscle fibers, and hence the spindles

Figure 4.5: Photo of the sensory part of the muscle spindle, in which the nerve ending is wrapped around the nuclear [27].

are lengthened and shortened together with the muscle fibers. Hence, the length and velocity of a muscle spindle are always proportional to the length and contraction velocity of the muscle fibers.

The nuclear bag and nuclear chain fibers contain multiple cell nuclei. As the naming suggest, in the nuclear bag fibers the cell nuclei are located in a bag-formed area in the middle of the fiber, and in the nuclear chain fiber the nuclei are located in a chain along the whole length of the fiber. Both the nuclear chain and nuclear bag fibers consists of two small muscles at the endings, and a sensory part in the middle. A nerve ending is wrapped around the sensory part, and essentially is sensitive to the stretch of the sensory part (Figure 4.5).

The small muscles inside the muscle spindle are called 'intrafusal' muscles (intrafusal means 'inside the spindle'). Hence, the normal muscle fibers outside the muscle spindle are called the extrafusal muscle fibers. The intrafusal muscle spindles are innervated by a separate motor neuron, the γ-motor neuron, which is an efferent innervation to the muscle spindle (carrying signals from the CNS to the periphery).

The nuclear bag fibers are sensitive to the stretch velocity, and the nuclear chain fibers are sensitive to the stretch length. There are two types of afferent nerves, Ia and II sensory nerves. The Ia sensory nerve receives branches from the sensors of both the nuclear bag and nuclear chain fibers, and thus contains length and velocity information. The II sensory nerve receives only branches from the nuclear chain fibers, and contains only length information. According to the specific sensitivity of the nuclear bag and nuclear chain fibers, the innervating γ-motor neurons are called γ_d (dynamic) and γ_s (static) motor neurons. In Figure 4.6 all efferent and afferent nerves connected to the muscle spindle are shown.

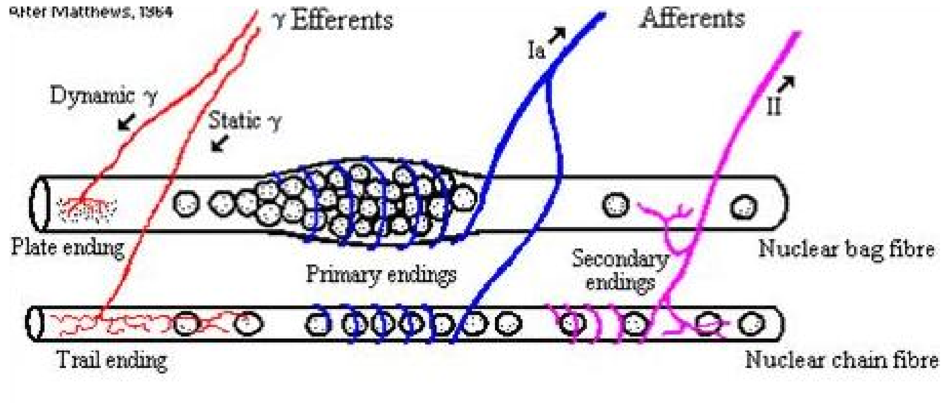

Figure 4.6: A muscle spindle has two efferent nerve inputs (γ_d to the nuclear bag muscle fiber and γ_s to the nuclear chain muscle fiber) and two afferent nerve outputs (Ia from both the nuclear bag and nuclear chain sensory parts, and II mainly from the nuclear chain sensory part)[28].

Figure 4.7: A block scheme showing the two mechanical inputs (length and velocity) and two neural inputs (γ_d and γ_s motor neurons), and two neural outputs (Ia and II afferent nerves) of the muscle spindle.

Figure 4.7 contains a block scheme in which all inputs and outputs of the muscle spindle are depicted. The muscle spindle has two mechanical inputs (length and contraction velocity) and two neural inputs (γ_d and γ_s motor neurons), and two neural outputs (Ia and II sensory nerves). Hence, the muscle spindle is a multi-variable system in which there is a non-linear interaction between the inputs.

4.1.3 Vestibulary system

The vestibulary system consists of three perpendicular semi-circular canals and an otolith system in each of the inner ears (Fig. 4.8).

The semi-circular canals are sensitive to rotational accelerations of the head. Since there are three perpendicular rotational sensors, any rotational movement of the head will be detected. The semi-circular canals are filled with fluid, and sealed off by a membrane (cupula) which prevents the fluid

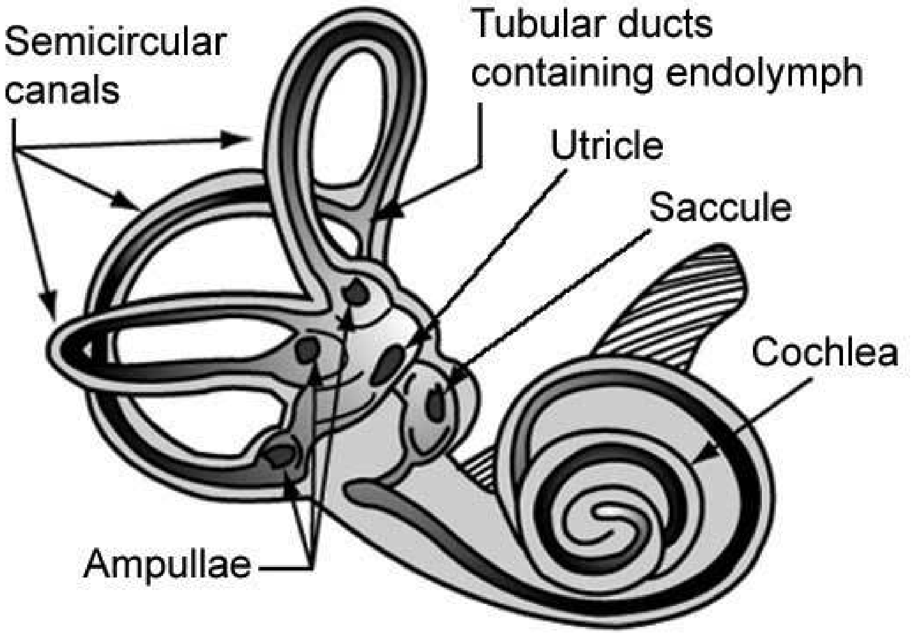

Figure 4.8: The three semi-circular canals in the vestibulary organ are sensitive to rotational accelerations, due to the mass-spring-damping properties of the fluid and the cupula, which closes the canal. The otolith near the center of the semi-circular canals is sensitive for translational accelerations and for gravitational forces [29].

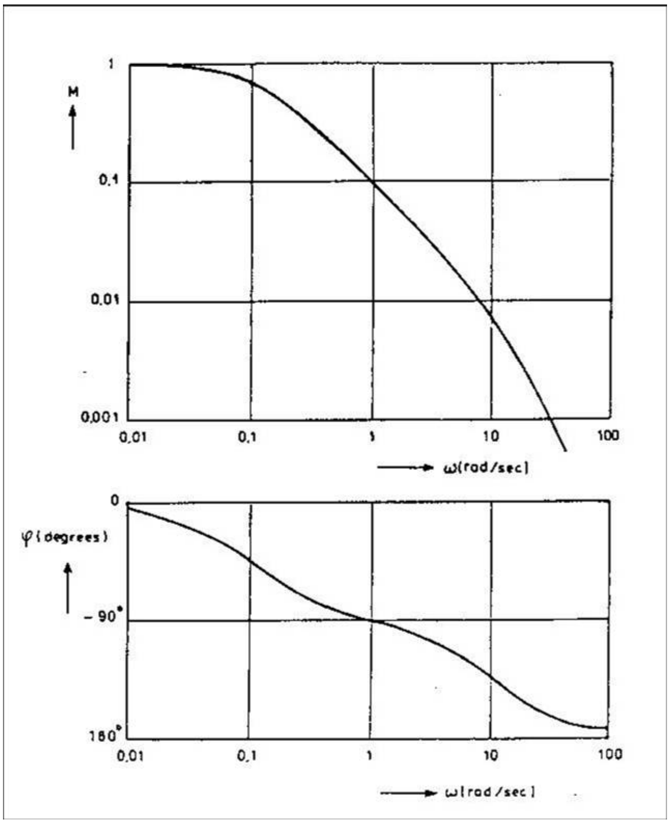

Figure 4.9: Transfer function in the frequency domain of the semi-circular canals: $H(\omega) = x_{cupula}(\omega)/\alpha(\omega)$, in which $\alpha(\omega)$ are the rotational accelerations. Between 0.1Hz and 10 Hz the transfer function approximates an integrator and the sensor output is proportional to rotational velocity [19].

flow around. The excursion of the cupula is sensed and transmitted to the CNS. Through the mass-spring-damper properties of the fluids and the cupula, the semi-circular canals act as rotational velocity sensors for an important range of frequencies, i.e. between 0.1 and 10 Hz (Fig. 4.9).

The orientation of the head can only be reconstructed through integration in time of the rotational acceleration. This will result in integration offset. This integration offset can be experienced when rotating with the eyes closed. After several turns, it is difficult to know one's orientation in the room.

Translational accelerations are being detected by the otolith system in the inner ear. The otolith system consists of small bone parts on little hairs. The amount of bending of the hairs gives an indication of the acceleration and weight of the bone parts. The otolith system gives information about the translational accelerations of the head, but the otolith system is also sensitive for gravity.

The perceived integration offset directly points to the role of the visual system, which provides direct position and orientation information of the head position. Humans are capable of deriving velocity information by the visual system (how fast an object is moving), but no acceleration information (changes of the speed of the object). The combination of the visual and vestibulary system provides position, velocity and acceleration information of the head. It is obvious that for the position of the rest of the body in space the relative position of the head with respect to the trunk must be detected by sensors in the neck musculature.

4.1.4 Tactile sensors

The skin is the boundary between the outside world and the inside body. One important function of the skin is protection against damaging influences from outside, like bacteria and viruses, and chemicals. Another function is the information exchange between the inside body and the direct environment. In the skin, sensory organs are sensitive for touching (mechanoreceptors), heat and cold (thermoreceptors) and pain (nocireceptors).

Tactile sensors in the skin provide information about the external forces, i.e. normal and shear forces at the skin. Humans are capable of sensing the forces under their feet, which is an important cue for postural control while standing. In addition, there are pressure sensors and temperature sensors. The shape of the sensor cells determines if they are more sensitive to certain deformations, and result e.g. in pressure or stretch sensors. The sensors are connected to nerves. Often more than one sensor is firing through the same nerve. The more a sensor is deformed, the higher the firing frequency will be in the nerve. In the hairy body regions, hardly any tactile sensors are present, and most information is detected by sensors around the hair roots. Most sensors are present in the non-hairy regions of the human body, like the hand palms and the foot soles.
The following sensory organs can be found in the (non-hairy) skin (Figure 4.10):

- Pacini corpuscles. These sensors are 2-3 mm big, and are located deep in the skin at the border of the dermis and subdermal layer. These tactile sensors are sensitive for light touching and small deformations and can also detect acceleration and vibration.

- Meisner corpuscles. These sensors are located in small clusters just under the epidermis, and are therefore typical touch sensors but can

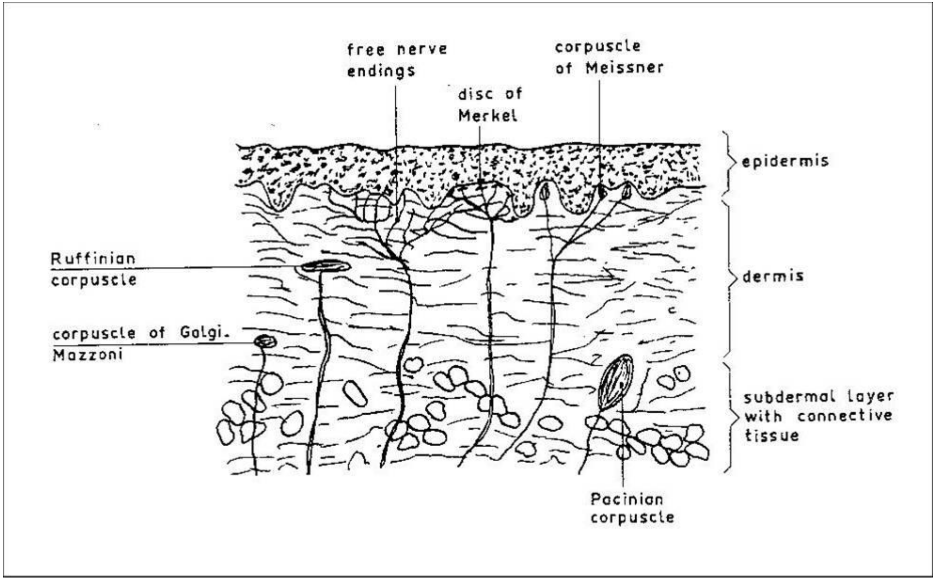

Figure 4.10: Cross-section of the non-hairy skin [19].

detect speed as well.

- Golgi-Mazzoni corpuscles. These sensors are located at the border of dermis and subdermal layer, and are sensitive to large deformation and pressure.
- Discs of Merkel. These sensors are located near the skin surface and are specific touch sensors.
- Ruffini corpuscles located in the dermis. There are two types of Ruffini corpuscles, one is sensitive for pressure, and the other is sensitive for temperature.
- ” Free nerve endings. These are the final branches of the nerves, and are not connected to sensory organs. They are only stimulated by large deformations, and are thought to be pain sensors.

Key to the understanding of human (and animal) motor control are the time-delays in the neuromuscular system, and the nature of the signals recorded (see Table 4.1).

Table 4.1: : Diameter and transmission speed of some of the proprioceptive sensors in the body.

	Diameter (μm)	Transmission speed (m/s)	Type of sensor	Stimulus
Ia	12 - 20	70 - 100	Muscle spindle	Length & velocity
Ib	12 - 20	70 - 100	GTO	Force
II	6 - 12	35 - 70	Muscle spindle	Length
	2 - 5	12 - 30	Pacini corpuscle	Pressure
	0.5 - 2	3 - 12	Free nerve ending	Nociceptive

Time-delays result in a considerable phase lag, and therefore velocity and acceleration information is needed to make up for some of the phase lag. As an example, due to the large time-delays, motions under visual control have a bandwidth of around 0.5 Hz, which is fairly slow. Most motions are not under visual control but under proprioceptive control of the muscle spindles and GTOs, which have time-delays in the order of 25 - 40 msec, and can provide feedback up to frequencies of 3 Hz (shoulder) to 6 Hz (wrist and ankle).

The 'redundancy' of the number and type of sensory organs calls for sensory fusion. One important paper considering sensor fusion in balance control during standing has been published by Van der Kooij et al. [30]. A Kalman filter was introduced to weigh the sensor information with the possible sensory noise. If a sensor is less accurate, or being perturbed (visual perturbations, decreased skin sensitivity due to e.g. diabetes, vestibular deficiencies), other sensors might provide the necessary information, and the contribution of sensors shift. However, the result will be suboptimal to the situation in which all sensors would be available. Sensors can take over each others contribution, but might have disadvantages in terms of dynamics and time-delays.

4.2 Feedback & reflexes

The neuromuscular system can be described in more detail as in Figure 4.11. Here the interaction between the intrinsic muscle properties (muscle stiffness and viscosity) and the reflexive muscle properties (length and velocity feedback through the muscle spindles, force feedback trough the Golgi Tendon organs) is shown, since they are both depicted as feedback pathways. The intrinsic feedback pathway has no time-delay and no actuator in the loop, is therefore passive and can not destabilize the system. The reflexive pathways do have an actuator (muscle) in the loop, and particularly due to the time-delays in the system, instabilities might emerge. The dynamic behavior of the neuromuscular system can be described by the admittance of the system. The admittance is the inverse of the system impedance, describes the effect of external forces on the position of the neuromuscular system (position over force), and incorporates the stiffness, viscosity and inertial properties, as well as the reflexive feedback properties. Experiments have shown that the dynamic behavior (admittance) of the neuromuscular system is mainly due to the reflexive properties of position, velocity and force feedback, which can rapidly be adapted inside the CNS.

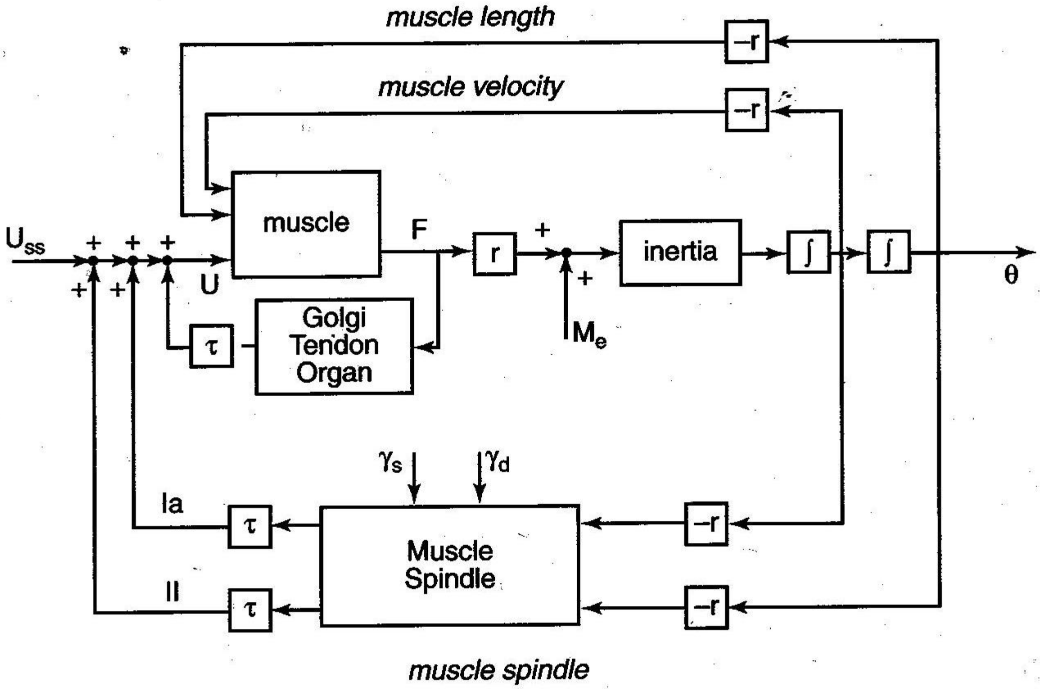

Figure 4.11: A general scheme of a musculoskeletal system and its proprioceptive feedback loops. Input u_{ss} is a supraspinal neural signal, the output is the joint angle θ. The moment arm r transfers muscle force into moment, and joint angle into muscle length. τ represent the time delay because of neural signal transport and processing. Joint angle and angular velocity are fed back through the intrinsic muscle properties (force-length and force-velocity relation) and through the muscle spindle, resulting in Ia and II muscle spindle afferents. The Golgi tendon organ is sensitive to muscle force.[19]

One of the most salient features of human motion control is the easy switching between position control and force control (position tasks and force tasks). For a position tasks, the admittance should be low (small effect of external forces on the final discussion), resulting in co-contraction of antagonistic muscles (increasing joint stiffness and viscosity) and high reflex gains for velocity and position feedback. The role of force feedback is still under debate. On the one hand, positive force feedback gains will increase reflexive position feedback, but negative force feedback gains will increase the intrinsic visco-elasticity.

Recent, unpublished experiments have shown either of the two possibilities when testing in shoulders and ankles. For force tasks the admittance should be very high, i.e. you should 'give way' to external perturbations in order to keep the force constant. Experiments have shown that human increase their admittance by negative position and velocity reflexive feedback gains and by high positive force feedback gains. The ability to switch between position and force tasks is the result of the impedance (admittance) control of the neuromuscular system, which switches between high and low admittance using the reflexive system. Basically this is a very low-level control system on the spinal cord level, which is tuned by supraspinal brain areas to the task at hand.

4.3 Feed forward & learning

Human motions are presumably partly under feedforward and partly under feedback control (see Figure 4.12). The bandwidth of the (position) feedback control system ranges from 3-4 Hz (shoulder) to 11-12 Hz for the wrist. Faster motions are completely under feedforward control, in that the cortex is directly sending activation signals to the muscles. For fast motions the reflexive feedback gains should be close to zero, otherwise the fast motion would be inhibited by the reflexive system. In Figure 4.12 a combination of a feedforward and feedback system is shown. The ideal feedforward system should be the inverse of the musculoskeletal system (including the environment if necessary). The feedforward system calculates the required muscle activation given the desired trajectory. If this muscle activation is actually input to the musculoskeletal system, the resulting trajectory will be close to the reference trajectory. Sensory feedback is very important for learning to execute motions. "You learn by making errors. Without errors you do not learn." Feedback Error Learning ([?]) showed that is was feasible to train the Feedforward model using the output of the feedback system. In the biological Neural Networks, sensory information is presumably going up to the cortical brain areas, where efferent and afferent information is compared between each other, and with the target result of the motion. Other learning schemes like reinforcement learning might also apply, but these schemes are less efficient since only information whether or not the goal is reached is provided.

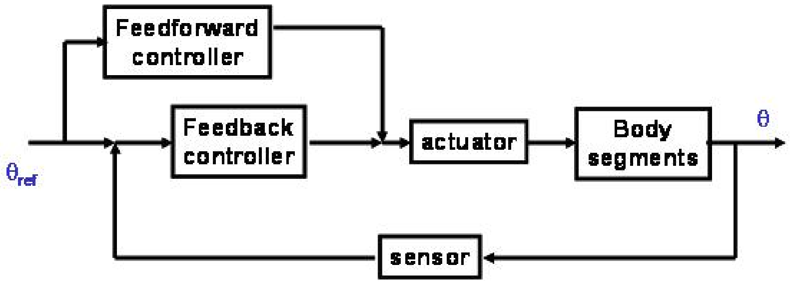

Figure 4.12: Motions are presumably controlled by a combination of feed-forward and feedback control [19].

4.4 Non linearities

In technological systems, most controllers are based on a linearized or piece-wise linearized representation of the system. In contrast, the CNS takes advantage of non-linear properties. In the neuromuscular system there are many non-linearities found, i.e. muscle stiffness and viscosity, reflexive feed-back, sensors, interneurons, etc. Analyzing non-linear controllers requires special techniques to derive the controller properties, like analyzing stable limit cycles, wavelet decomposition, non-linear parameter estimation. Only fragmentary knowledge is available about the effect of the non-linearities in the neuromuscular system on the final behaviour. Training experiments with artificial Neural Networks as non-linear controllers have shown that for a Neural Network it does not make a real difference if a linear or a non-linear system is to be controlled. One might extrapolate from these experiments that also the CNS can deal effectively with non-linearities.

4.5 Special Reflexes

Reflexes are state event triggered muscle contractions. Their sensitivity usually depends on the state and phase of the musculo skeletal system. Reflexes can be modulated by the higher brain areas. They are usually found on a 'low control level' (in humans on spinal cord level), and are therefore quite fast control mechanisms in biological systems. Some different type of reflex functions can be found.

We have seen in Section 4.2 that reflexes are an integral part of the neuromuscular control system, which especially serve to resist against low-frequent perturbations during postural tasks. Another protective reflex is found in the human shoulder. A soft sensitive ring in the gleno humaral joint, called the labrum, is assumed to work as a sensor that prevents dislocation of the shoulder joint by activation of stabilizing muscles through cross-reflexes from connective tissue to muscles.

Another kind of reflexes found in the human eye is the saccades. These are the fast eye movements that aim the fovea (the high resolution area of the retina) on the areas of interest. These scanning movements are so fast (up to 700 deg/s.) that humans hardly notice them. A memory effect is required to remember the scene, so that for the brains the illusion is created that a uniform high-resolution image of the scene is available. The main advantage of this control mechanism is that an accurate image of the scene is obtained by combination of a rough sensor (the magula) combined with a small high-resolution sensor selectively zooming in (the retina).

Reflex type of control can induce oscillations, and can be used for dynamic tasks such as flapping of wings. Some insects require flapping frequencies up to 1000 Hz. These high flapping frequencies require special neuro muscular solutions. It has been shown that these insects have special vibrating muscles that act reflexively to keep the wings in their natural frequency. A variety of flexible elements in the insect's body act as springs. So basically the system acts as a mass spring system, being activated only once a cycle.

Chapter 5

Conclusions

The mechanisms found in biology in the previous chapters are discussed in Table 5.1 and Table 5.2

5.1 General benefits of biological joints

In Table 5.1 an overview is given of the mechanisms found in Chapter 2, 3 and 4.

Table 5.1: Overview of biological mechanisms in space applications. Interesting mechanisms for space applications are given in red.

Nr.	Ch.	Description	Function
1.	2.1	Jet propulsion	Effective propulsion with muscles
2.	2.1	Longitudinal muscles on hydroskeleton	Shortening of tube-like structures
3.	2.1	Unilateral muscles on hydroskeleton	Bending of tube-like structures
4.	2.1	Circular muscles on hydroskeleton	Lengthening and flattening of tube-like structures
5.	2.1	Transverse muscles on hydroskeleton	Flattening of hydroskeleton structures
6.	2.1	Oblique muscles on hydroskeleton	High-power density muscle arrangements
7.	2.2	Joints with thin and thick exoskeleton	Protective solid state joint structural support
8.	2.2	Pressure increase hydrostatic limb flexion	Centralized power generation
9.	2.2	Muscles inside an enclosure	Protective shell with mechanical sliding parts

Continued on next page

Table 5.1 – continued from previous page

Nr.	Ch.	Description	Evaluation
10.	2.3	Endoskeleton joint types	Seven different joint types
11.	2.3	Endoskeleton bone/tendon clusters	Compact joints for complex functions
12.	2.3	Bony end stops	Workspace limitation
13.	2.3	Lubricating layers	Low friction sliding
14.	2.3	Synovial fluids and bursea	Joint fluid storage
15.	2.3	Tendon guiding tunnels	Low friction mechanical energy transport
16.	3.1	Muscle configurations	Scaling force/length ratios
17.	3.2	Return spring	Muscle (actuator) reduction
18.	3.2	Spring weight compensation	Work/energy reduction for quasi static tasks
19.	3.2	Legs as bouncing sticks	Work/energy reduction for dynamic tasks
20.	3.2	Spines as energy storage	Work/energy reduction for dynamic tasks
21.	3.2	Click mechanism of wings	Shaping of dynamic load profile
22.	3.2	Oscillating wing mechanism	Flap frequency increase
23.	3.2	Catapult effect	Energy boosts
24.	3.3	Poly-articular muscles	Distribution of muscle work over joint
25.	3.3	Poly articular tendons under actuation	Muscle reduction of multi-dof movements
26.	3.3	Ligaments as end stops	Workspace limitation
27.	4.1	Neuromuscular feedback	Always stable motion control in spite of time delay
28.	4.1	Task optimization	Task related control performance increase
29.	4.2	Neuro muscular reflexes	Workspace related control gains
30.	4.3	Feedforward and learning	Upgrade system performance by learning
31.	4.4	Muscle activation optimization	Optimizing multi-DOF system performance
32.	4.5	Labrum reflexes	Cross-reflexes for complex stabilization
33.	4.5	saccades of the human eye	Low level signal pre-processing
34.	4.5	results in stable limit cycles with adaptive frequencies	High frequent motion control

5.2 Candidates for space applications

In Table 5.2 an overview is given of the mechanisms found related to the space requirements formulated in Chapter 1.

Table 5.2: Overview of biological mechanisms for space applications

Nr.	Ch.	Description	Evaluation
1.	2.1	Jet propulsion	Only works for liquids and gasses. Not applicable in space
2.	2.1	Longitudinal muscles on hydroskeleton	Hydroskeletons have interesting properties because of the compact system in a package approach and the dexterity. Also the range of motion can be scaled by design. The enclosed approach is a benefit as well.
3.	2.1	Unilateral muscles on hydroskeleton	
4.	2.1	Circular muscles on hydroskeleton	
5.	2.1	Transverse muscles on hydroskeleton	
6.	2.1	Oblique muscles on hydroskeleton	
7.	2.2	Joints with thin and thick exoskeleton	The advantage of this mechanism is that it has structural stiffness with degrees of freedom only where desired.
8.	2.2	Pressure increase hydrostatic limb flexion	Hydraulics-based actuation is not desired in space due to out gassing problems.
9.	2.2	Muscles inside an enclosure	Hinging rigid elements moved by muscles implies a simple and robust mechanical structure.
10.	2.3	Endoskeleton joint types	Seems fragile and require lubrication
11.	2.3	Endoskeleton bone/tendon clusters	Very complex for applications
12.	2.3	Bony end stops	Causes high local material stresses and joint loads
13.	2.3	Lubricating layers	Types of materials in space are restricted. This is a materials issue.
14.	2.3	Synovial fluids and bursea	Performance depends heavily on material combinations, and might not work in space. Out gassing danger.
15.	2.3	Tendon guiding tunnels	Useful to construct slender mechanisms and place the actuators somewhere else (e.g. inside the rover)

Continued on next page

Table 5.2 – continued from previous page

Nr.	Ch.	Description	Evaluation
16.	3.1	Muscle configurations	Might be useful in a later phase. First see what actuator is applied and what load diagram is required.
17.	3.2	Return spring	Reduces the number of required actuators but one actuator always works against the other. This requires energy.
18.	3.2	Spring weight compensation	This enables systems to move masses with little energy and power, which reduces actuator requirements.
19.	3.2	Legs as bouncing sticks	Works only for cyclic tasks
20.	3.2	Spines as energy storage	Works only for cyclic tasks
21.	3.2	Click mechanism of wings	Works only dynamic tasks
22.	3.2	Oscillating wing mechanism	Works only for cyclic tasks
23.	3.2	Catapult effect	Is mainly for energy accumulation and high-power energy bursts
24.	3.3	Poly-articular muscles	Coupling of degrees of freedom can bring a simplification of system complexity
25.	3.3	Poly articular tendons (under actuation)	
26.	3.3	Ligaments as end stops	Is an option for motion restrictions of joints
27.	4.1	Neuromuscular feedback	Time delay is not an issue in space systems.
28.	4.1	Task optimization	Switching between force and position control can be of benefit. However, in this stage not yet relevant.
29.	4.2	Neuro muscular reflexes	in terms of response speed and autonomy it can be beneficial
30.	4.3	Feedforward and learning	This is an interesting topic, once the system is designed. However, this is a topic on its own.
31.	4.4	Muscle activation optimization	Only works when there are more actuators than degrees of freedom. Probably not an issue.
32.	4.5	Labrum reflexes	This intelligent overload sensor is easier realized in metal.
33.	4.5	saccades of the human eye	Could be interesting for motion of vision systems
34.	4.5	reflexive induced oscillations	Only interesting for cyclic tasks

5.3 Proposed planning for the project

Several classes of mechanisms found in biology came forward as interesting for possible space applications. These were:

1. Hydroskeleton (Nr. 2 till 6)
2. Exoskeleton (Nr. 7, 9)
3. Tendon Guiding tunnels (Nr. 15)
4. Spring weight compensation (Nr.18)
5. Poly-articular muscles and tendons (Nr. 24, 25)
6. Feedforward and Learning (Nr. 30)

Biological control systems are distributed systems, i.e. dynamic (non-linear) properties aiding to the control are distributed amongst actuator, plant and sensor properties. The Central Nervous System takes advantage of these properties, and adds its own non-linear control properties to it, like asynchronous and massive parallel processing of data. In contrast, in technical systems often little effort is put in the design of the actuators, plant and sensors, or only the linearized properties are taken into account, whereas the controller should make up for all unwanted properties of the components and the desired properties of the system.

Mechanisms 3 till 6 are not further investigated since this study focusses on joint design. Mechanisms 1 and 2 on the other hand are interesting and further examined in Part II of this report.

Part II

A New Robotic Joint Design

Chapter 6

Joint Design

From Part 1 of this study two classes of mechanisms found in biology came forward as interesting for possible space applications. These were:

1. Hydroskeleton
2. Exoskeleton

These mechanisms will be further examined to use them as an inspiration to come to a design of a new robotic joint.

6.1 Joint Structure

This paragraph will give an overview of literature found of hydroskeleton and exoskeleton types of mechanisms in robotics. Several actuators inspired by biologic mechanisms were discussed as well. From this literature a concept design of a robotic joint is proposed.

6.1.1 Snake-like robots

In a study of biologically inspired robots we found that many research groups make snake-like robots [31] [32] [33] [34] [35] [36] [37]. Most of them follow a segmented approach, with hinges between segments. A few groups try to make real snake-like or worm-like actuation schemes. In one publication continuum robots are mentioned because there is not a single joint, but many, or even the whole structure can deform.

6.1.2 Exoskeletons

Exoskeletons in medical literature have a different meaning than in biology. Where in biology it means having a rigid, closed external framework, in medical literature exoskeletons are most often implemented as rehabilitation devices for support or as teleoperation mechanisms [38]. An example of exoskeleton is the Roboknee [39]. The roboknee is meant to learn more about human movement and to enhance human strength. The roboknee uses new piezoelectric ultrasonic motors (USM) for light-weight and high torque actuation in planetary environments. Other types of exoskeletons found are most often complex and heavy with many actuators [40].

To follow the exoskeleton definition from biology, mechanisms in other applications were studied. Interesting structures that were found are bellows, because they are light, torsion stiff, but easily bendable in order to function as a joint. Bellows are used as connections between pipes or rotating axles. Sometimes gas under high pressure is being carried in those pipes, so the bellows can be made to be sealed for gas. Bellows come in a wide variety (see Figure 6.1), but for application in a joint they may have to be specially designed. When bellows are used as an exoskeleton and actuators are used inside to make the bellows bend, an interesting joint could be formed. Very little information about Bellows used in this way was found, so modeling and experiments have to be done to see how the bellows will bend and behave upon (contraction) actuators inside.

Figure 6.1: Different types of bellows

6.2 Actuators

In order to actuate an exoskeleton consisting of a bellows, special actuators must be developed. Artificial muscle types are interesting since there are no rotating parts so that lubrication for instance is not necessary. Biologically inspired actuators for space applications are studied in earlier documents of the Ariadna framework [41] [42]. There is a wide variety in artificial muscles with different characteristics as shown in Table 6.1. In this section two interesting actuators in which the actuation material changes shape when an electrical current or voltage is applied, are discussed: electro active polymers and shape memory alloys.

Table 6.1: Overview of characteristics of different actuators [43]

Actuator Type (specific example)	Maximum Strain (%)	Maximum Pressure (MPa)	Specific Elastic Energy Density (J/g)	Elastic Energy Density (J/cm^3)	Maximum Efficiency (%)	Relative speed full cycle
Electroactive Polymer Artificial muscle						
Acrylic	215	7.2	3.4	3.4	60-80	Medium
Silicone (CF19-2186)	63	3.0	0.75	0.75	90	Fast
Electrostrictor polymer (P(VDF-TrFE))	4	15	0.17	0.3	-	Fast
Electrostatic Devices (Integrated Force Array)	50	0.03	0.0015	0.0015	> 90	Fast
Electromagnetic (Voice Coil)	50	0.10	0.003	0.025	> 90	Fast
Piezoelectric						
Ceramic(PZT)	0.2	110	0.013	0.10	> 90	Fast
Single Crystal(PZN-PT)	1.7	131	0.13	1.0	> 90	Fast
Polymer(PDVF)	0.1	4.8	0.0013	0.0024	n/a	Fast
Shape Memory Alloys (NiTi)	> 5	> 200	> 15	> 100	< 10	Slow
Shape Memory Polymer	100	4	2	2	< 10	Slow
Thermal(Expansion)	1	78	0.15	0.4	< 10	Slow
Electrochemo-mechanical Conducting Polymer (Polyaniline)	10	450	23	23	< 1	Slow
Mechano-chemical Polymers/Gels (polyelectrolyte)	> 40	0.3	0.06	0.06	30	Slow
Magnetostrictive (Terfenol-D. Etrema Products)	0.2	70	0.0027	0.025	60	Fast
Natural Muscle (Human Skeleton)	> 40	0.35	0.07	0.07	> 35	Medium

6.2.1 Electroactive polymers

One of the newest fields in biologically inspired actuators are electro active polymers (EAP). Electro active Polymers are polymers whose shape is modified when a voltage is applied to them. EAP devices are classified as either ionic or electronic, based on the method of charge transfer used. They can be used as actuators or sensors. As actuators, they are characterized by the fact that they can undergo a large amount of deformation while sustaining large forces. Due to the similarities with biological tissues in terms of achievable stress and force, they are often called artificial muscles, and have the potential for application in the field of robotics, where large linear movement is often needed. Research on possible applications in space of EAP material is done as well [44] [45] [46].

6.2.2 Shaped memory alloys

Shaped memory alloys (SMA) could be a very interesting material to act as an actuator. An SMA undergoes a pronounced deformation to a remembered shape when its temperature rises through a transition value, causing a transformation in its metallurgical structure from a martensitic to an austenitic phase [47]. This generates a large force. The principle of using a SMA as an actuator was found in the latch-release pin puller from Nasa Lewis Research Centre. See Figure 6.2.

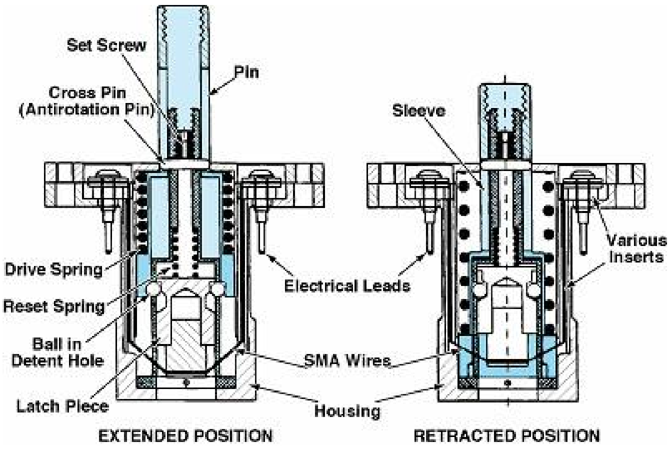

Figure 6.2: SMA-Actuated Pin Puller where the SMA wire serves as a trigger that releases potential energy stored in the driver spring [47].

Motion control could be a problem since there is hysteresis present. Not much literature has been written on how to control the contraction of the SMA material. A paper on accurate length control on SMA wires was found [48] and we may be able to use the same technique in the joint design if

SMA wires are used. SMA material is as mentioned before, more accepted in space technologies and therefor seems for actuating the new robotic design the best option. The disadvantage of the complex control will be considered as a problem that can be solved. The slow contracting and restoring cycle is not a problem in space. A big problem however is, that it can only contract 5-7% of its length maximum. This problem of limited strain can however be solved by using helix-wound SMA made of nickel/titanium alloy denoted by the trade Nitinol. Two companies were found that make spirals out of SMA (Niti springs) that can contract up to 60%:

1. www.robosoft.fr. (Mondotronics springs)
2. www.robotstore.com. (Mondotronics springs)

The coil diameter of these Niti springs is 6 mm, and wire diameter is 750 m. The maximum generated force is about 3-4 N. Actuation current is 2A. Heating results in 'contraction' of the spring. When cooled the zero length is about 2.5 - 3.5 mm. There is a considerable hysteresis in the cool state. When hot, the zero length of the spring decreases to 16 mm. The spring stiffness is relatively constant between the cool and hot state.

6.3 Proposed design

We propose a segmented setup, that will have a worm-like appearance. As an exoskeleton a bellows will be used to provide strength and acts as protection for the actuators inside.

The segments will have shape memory alloy springs (NiTi) as contracting actuators. Since the actuators as well as the bellows are compliant, the point of rotation (hinge) is unknown and can have different positions. Experiments and modeling need to be done to get an impression how this joint will behave and what the working range will be. An artist impression of the joint is given in Figure 6.3.

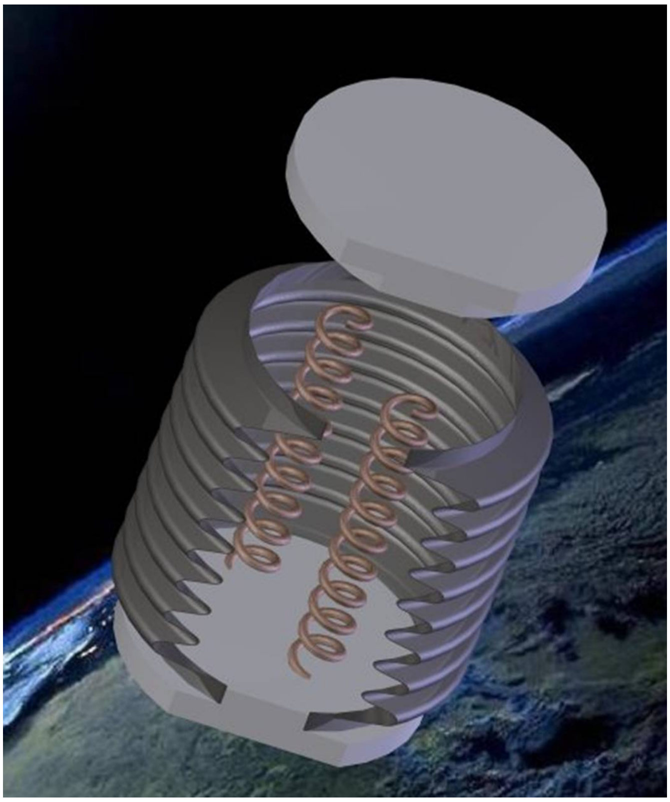

Figure 6.3: Art impression of proposed joint setup

Chapter 7

SMA measurements

The previous chapter showed that designing a joint with a bellows as exoskeleton and NiTi's as actuators could be an interesting option for space applications. This chapter will look deeper into the characteristics of the NiTi's and bellows by modeling and testing.

As no information was given about the NiTi spings beyond the fact that it can contract under a load of 3N, experiments that give an indication of the spring constant and other properties of this special spring were done with NiTi springs that are commercially available.
The equation of an ideal spring to approximate the spring constant k will be used:

$$F = k(u - u_0) \tag{7.1}$$

Figure 7.1 shows the spring, and the distance that is used as the length.

7.1 Load-length relation

In order to determine spring constant k from equation 7.1, an experiment was done with the setup shown in Figure 7.2. The experiment started with a heated spring with a load of 100 grams. The length of the spring was $19mm$ at that moment. When a load was applied on the wire that was attached to the spring, the spring extended, and the length could be measured. Loads of 100, 200 and 300 grams were used.

The following steps were taken, and the length was measured after each step:

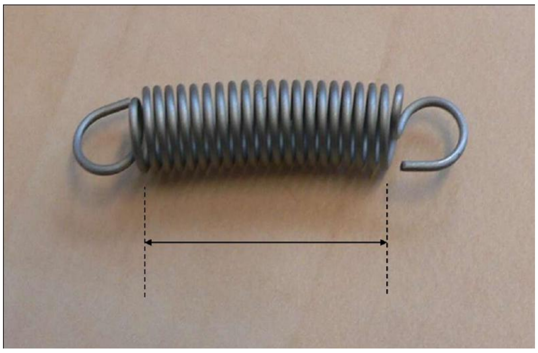

Figure 7.1: A spring of Nitinol material. When cool it can deform, and when hot, it contracts and straightens to the shortest length. The length measured in several experiments is the distance between the first and last coil of the spring.

- Let it cool down with the 100 gram
- Remove the weight
- Add a weight of 200 gram
- Remove the weight, and add a weight of 100 gram
- Remove the weight
- Add a weight of 300 gram
- Remove the weight, and add a weight of 200 gram
- Remove the weight, and add a weight of 100 gram
- Remove the weight

In Figure 7.3 the measured lengths are set out against the weight. The starting point is the point at length $19mm$, when the material is hot. When the material is cooled down the length will increase to approximately $31mm$ under a load of 100 grams. When the weight is removed, the length will decrease as shown in Figure 7.3.

The spring constant is calculated from the measurements done in the cool stated using the various load conditions. In Figure 7.3 three lines are shown with almost the same slope. Despite the zero length is changed after a larger load was applied, the spring constant does not change, and is around $0.245N/mm$. This spring constant will be determined more accurate later on.

As mentioned in Figure 7.3 it can also be seen that the zero length changes

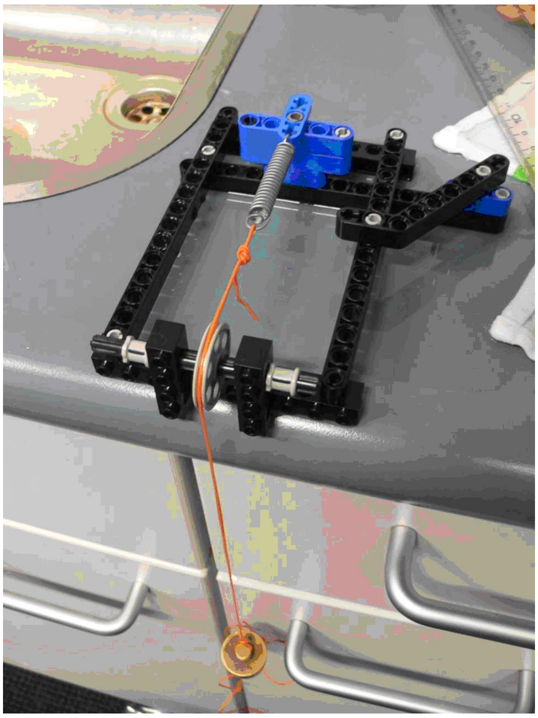

Figure 7.2: Simple experimental setup to roughly estimate the spring's properties.The weight pulls the wire, which extends the spring. Water of 60 degrees Celsius is used to contract the spring.

considerably in the cooled state. There is a large hysteresis. What is not shown is that when the spring is externally compressed beyond its current rest length u_0 the value of u_0 will decrease again. This is a rather peculiar plasticity property. The relationship between zero length and temperature is thus not linear, and depends on the previous stretching conditions. A formula describing this relation could not be found yet.

The method of heating and extending that was used in the previous experiment is not the realistic application, as the spring will be heating and cooling down under a load. Therefore more tests were done, each with the following steps:

- Apply a load of 0, 100, 200 or 300 grams
- Heat the NiTi spring and measure the length
- Let it cool down, and measure the length
- While the load > 0 grams, reduce the weight by 100 grams and measure the length

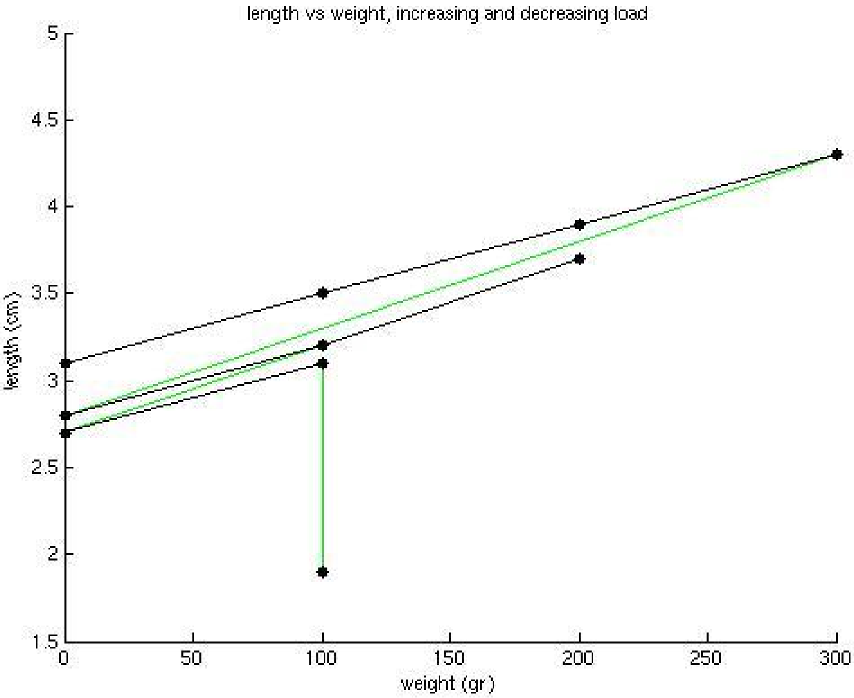

Figure 7.3: Measurement results for the load-length relation. Starting point is the point at $19mm$ length. The vertical line shows the cooling process. The solid black lines show the connected points when removing weights. The dashed green lines show the deformation when adding a weight

In Figure 7.4 the measurements are shown in a graph. The bottom line is the weight/length curve for the NiTi sping when hot. The other lines show the different lengths under the same load, but with other maximum starting loads applied to the spring.

In Figure 7.4 the lines look the same as in Figure 7.3, but although the spring constant is the same, the value of u_0 (0 weight) is clearly larger. It seems that cooling under different strains results in different rest lengths. The rest length in the zero load hot condition is repeatable, as well as the length in loading conditions. Still there doesn't seem to be a function that describes u_0. Probably the u_0 in realistic situations cannot be calculated, even when the maximum weight is known. What can be done however, is for different designs of the actuator, measure the length of the wires upon heating and cooling, to determine the operating range. A controller will then be necessary to hold a certain position.

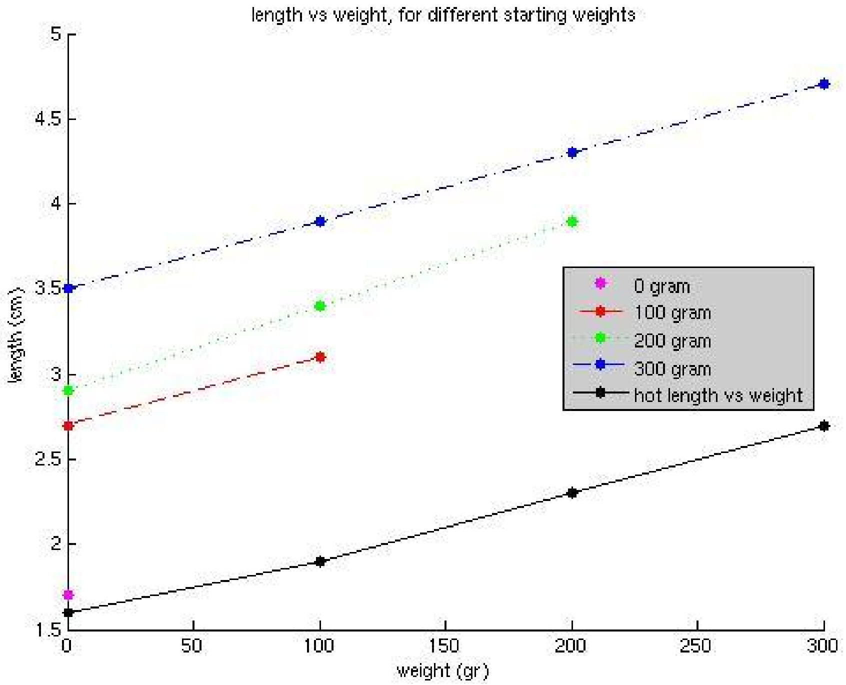

Figure 7.4: Four measurements on length change when removing weights. In each measurement the starting weight when heating and cooling the NiTi spring was varied. The values when the NiTi was hot were given a separate line, the solid black one.

7.2 Transition point; u_0 due to heating and cooling

Another experiment was done to determine the transition temperature of the NiTi and to find a relation between temperature and rest length u_0. The NiTi wire was placed in a MDA Q800 machine (see Figure 7.5). It has force, position and temperature control. The force on the piston is measured with an error less then a milliNewton while its movement is being controlled.

Since the machine has an operating range of $20mm$, there was a limitation in applying forces. The data sampling rate was set to 10 samples per second, so the lines in the following figures are due to the many points we have measured.

In the experiment we set a force of 1.5N and the temperature was increased from $38°C$ to $70°C$. After a few minutes the temperature was decreased again to $32°C$. In figure Figure 7.6 the displacement (arbitrary offset) is plot against temperature to show the hysteresis in the transition.

The transition process takes time and the process is quicker when a high

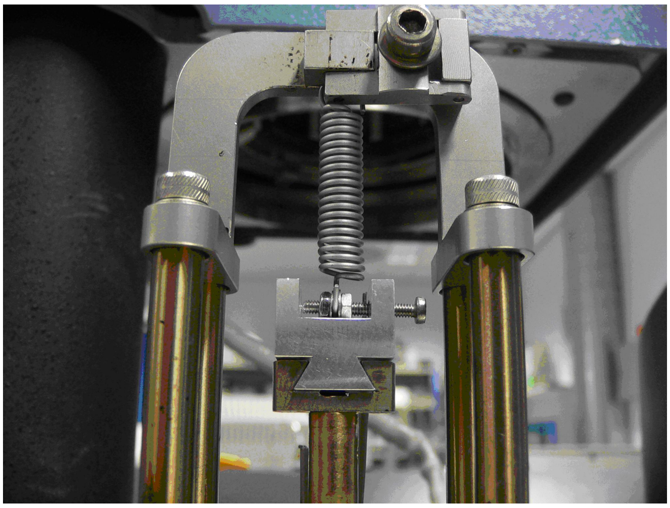

Figure 7.5: The NiTi spring mounted in the DMA Q800. In the top, the spring was attached via a clamp to the device. The clamp only hold the 'eye' of the spring. The spring was attached to the aluminium block using a screw as axle The piston below that, extends into the actuator and measurement part of the machine. A heater can be placed over this setup to control the temperature

temperature is presented on the material. This cannot be deduced from the figure, because a fixed temperature rate of 2 degrees per minute was used. An interesting part of the figure is the more or less linear line when cooling to room temperature. It can be concluded that this process is very slow in that area. It was noticed that when pouring cold water over the spring it extends much faster.

The transition of the shape memory alloy occurs between 42 and 52°C, has roughly the same pathway for cooling and heating, but the actual transition temperature depends on the tension in the spring (and hence on the load attached to it). The SMA spring has many properties comparable with human muscles. A controller should be able to take these properties into account, or even make use of them.

7.3 Increasing and decreasing force cycles

The first measurements were done again with many more points. The spring was heated and cooled without a load. Then a number of cycles from 0N to a force and back to 0N were done. The first cycle went to 0.5N. Then the

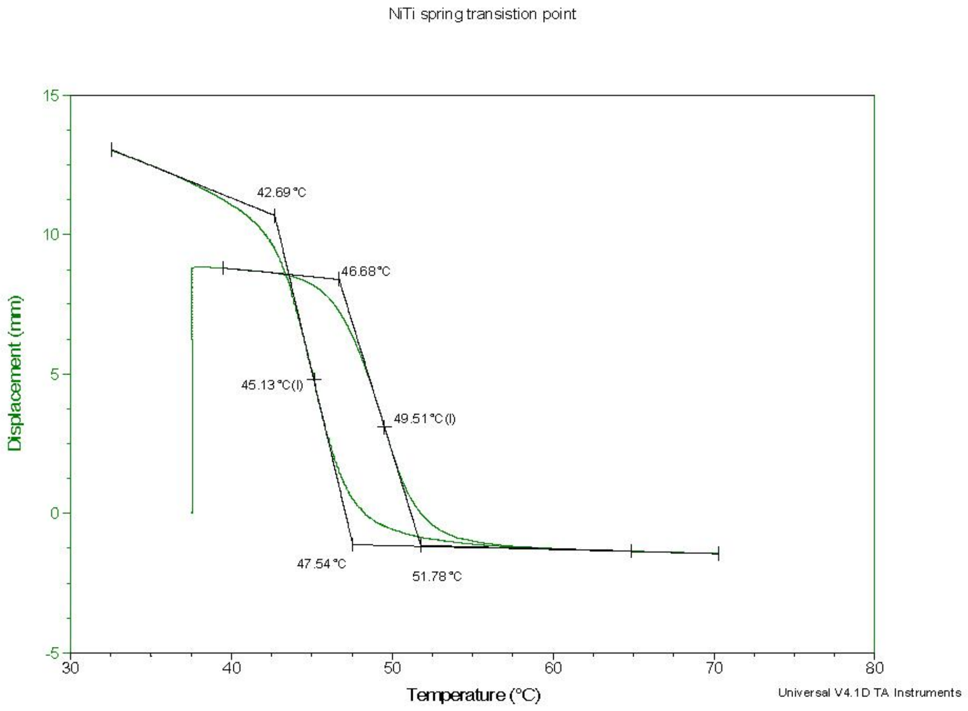

Figure 7.6: Hysteresis measurement of the NiTi spring regarding temperature. The vertical line shows increasing the load from 0 to 1.5N just before heating. Upon cooling the spring extended more then the machine could measure.

maximum force at each cycle was increased with $0.5N$ up to $3N$. However, the machine could not cope with the displacement around $2.2N$.

In Figure 7.7 the cycle from $2N$ to $0N$ to $3N$ is going through the same point at $2N$. This gives proof to the observation that the rest length doesn't change when the maximum force does not change. When the maximum force does change, an increase in the rest length is seen and no change in the spring constant. Looking at the top-peak of the cycles a possible relation can be found. This will not be analyzed in this study, but it could be interesting to determine this relation later.

Summary NiTi properties

Looking at the properties of the NiTi spring, it is seen that the rest length of the spring changes, while the stiffness is constant.

Table 7.1 gives the properties of the Niti springs found from the measurements.

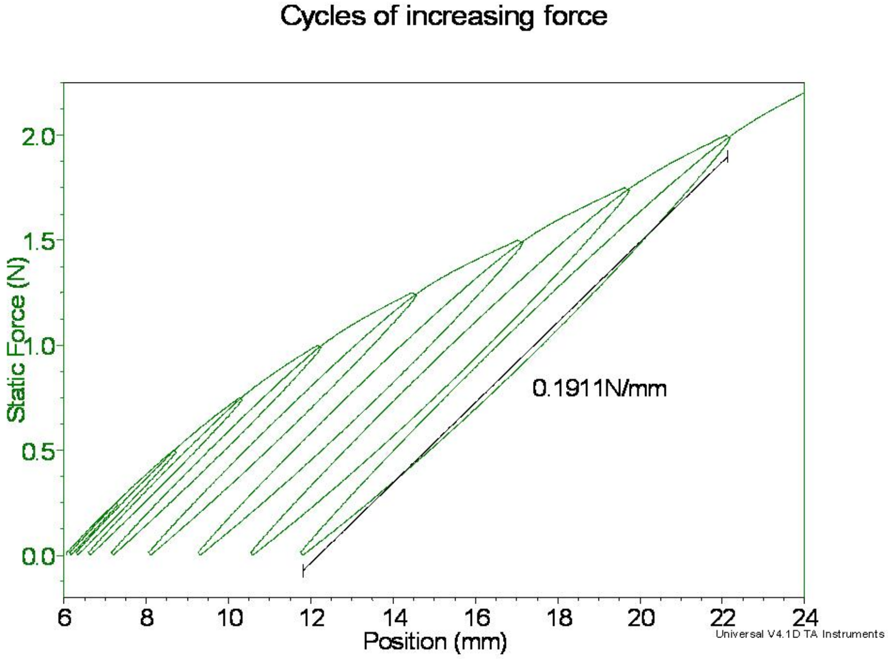

Figure 7.7: Under force control, the force was cycled from $0N$ to an increasing maximum force and back to $0N$. The hysteresis may be the result of inertia because the rate was constant at $0.125N/sec$. The spring stiffness is determined to be $0.1911N/mm$

Table 7.1: Niti properties

$u_0(hot)$	16.8 mm
C	0.1911 N/mm
$u_0(t)$	unknown function

Niti springs have several properties that can be an advantage or disadvantage for use in space. Several are listed below.

Pros:

- NiTi's can be "reset" by heating them
- Actuators can be set in parallel to provide a force greater than 3N
- NiTi springs can be added or taken away to increase or decrease the stiffness in the vertical direction and actuated rotations, which increases or decreases the possible payload

Cons:

- Stability in transverse direction of the spring should be provided by an exoskeleton.
- When a NiTi is compressed externally the spring will deform and thereby have a change in properties as well.

Chapter 8

Modeling & Optimization

Modeling and optimization are necessary to predict how the new robotic joint will behave. This chapter will describe a simple 2D model for a first impression of that.

8.1 Joint layout

In the Figure 8.1, two actuators (SMA, Niti springs) are drawn. Three or four of them are needed to be able to bend in two directions. A wide variety of NiTi spring arrangements within the bellows could be possible for different rotations and generated forces. The muscle architectures that were shown in Figure 3.2 can be an inspiration for that. For the model the NiTi springs as they are commercially available are used as an input, with the properties found in Chapter 7. A simplified 2D situation is used to model the behavior of the joint.

In unloaded condition the NiTi spring can contract up to 2 cm. Therefore the space between the NiTi springs should be 2 cm to enable a rotation angle of 45°. An exoskeleton can serve for protection, but it should rather not apply a moment that counteracts the rotation. If an exoskeleton will apply a moment on the NiTi springs, it should be compensated, otherwise the range of rotation will decrease.

When loaded with 3N, the length of the spring is 4.3-4.6 cm (Figure 7.3 and Figure 7.4). When hot, the length with a load of 3N is 2.6 cm. The change in length will then be between 1.7 and 2 cm, so that should be the distance between the NiTi springs to enable a rotation of 45°. Niti Springs can be used as an actuator in a bellows, but a pilot experiment is necessary to check whether the SMA can actually be controlled.

The Bellows will exert a small straightening moment depending on the

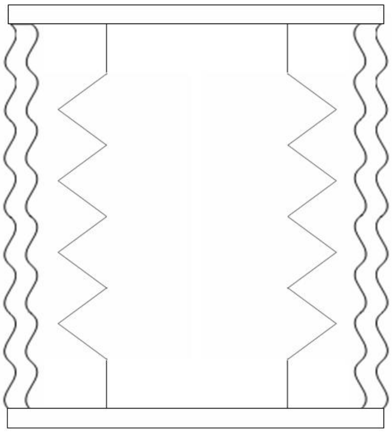

Figure 8.1: Joint lay out

design, whereas the rotational movement is very compliant.
One flaw of the torsion stiff joint is that a rotation around the an axis perpendicular to the spring is still possible in the actuated case, and the NiTi springs have to compensate that. So in general, the stiffness for all 3 rotations comes from the NiTi springs. This in turn means that if the springs need to compensate an external force, that force cannot be used to actuate the rotation. So the range of possible rotations will decrease. Placing the springs closer together will remedy this problem, but will also decrease the moment that the springs can compensate.

A challenge is to control the rotation angle, because in this case, the opposite springs counteract each other a bit. Let's review the situation that one spring is fully actuated, and then slowly cools down. At first, the force on the actuated spring is 3N. But as the actuated spring extends, the force decreases until equilibrium is found. For certain that will not be the situation at 0° rotation. The mirrored situation exists if the other spring is actuated, so there is not one unique rotation for the non-actuated situation. Therefore, a feedback controller that has knowledge of the current angle has to be used.

Because the material is bendable, the sideways stiffness is small that make large deflections possible. The Bellows can be compressed which can result in a smaller operating range since some of the actuation force will be used for this.

The Bellows will extend when a heavy payload is used, so the Bellows should be designed such that in the non-actuated case, there is not a large force acting on the NiTi springs.

As the point of rotation is not fixed, the moment exerted by the rotated payload cannot be compensated anymore. This again means a reduced operating range. The biggest problem is how to determine the design parameters such as the distance between the NiTi springs, as those are crucial for the operating range. Properties of bellows used in this way are very limited. The calculations to determine how the bellows will bend are difficult and simplifications are necessary.

8.2 Modeling

In the presented model of the bellows different stiffness' for compression and bending were set. The stiffness for compression was set very high.
We model the bellows in 2D with two springs at the sides as seen in Figure 8.2. We assume that the bellows will bend along a circle, so at the point of attachment with the flange, the angle is fixed. To simplify the calculations, the payload is neglected for now. Because the system is symmetric along the horizontal axis, only the upper part is shown.

Suppose a situation in which the bellows is bend. The moment the NiTi springs exert is dependent on the difference in force(ΔF), which is dependent on the difference in length of the NiTi springs. This difference can be calculated to be:

$$\Delta u_{niti} = u_{niti,left} - u_{niti,right} = 4d\sin(\alpha) \tag{8.1}$$

$$\Delta F_{niti} = k_n(\Delta u_{niti} + \Delta u_0) \tag{8.2}$$

$$M_{niti} = d\Delta F_{niti} \tag{8.3}$$

with,

$$\Delta u_0 = u_{0,hot} - u_{0,cool} \tag{8.4}$$

Using the maximum bending angle α_{max} and rewriting the formulae, we get:

$$M_{niti} = d \cdot k_n(4d\sin(\alpha_{max}) + \Delta u_0) \tag{8.5}$$

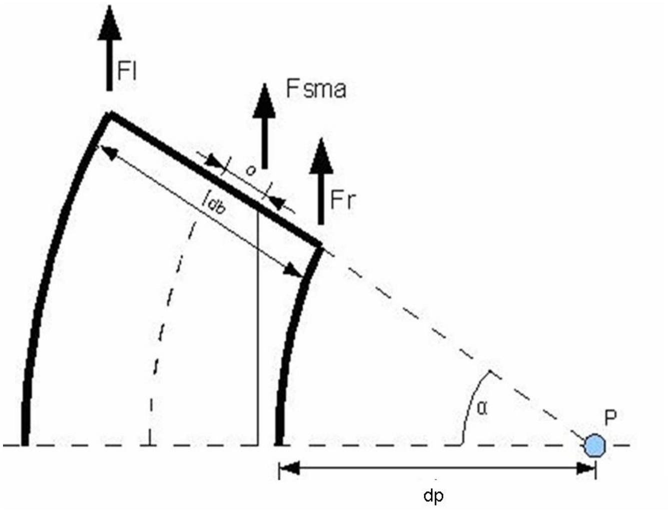

Figure 8.2: Schematic view of the NiTi springs inside the Bellows. The left and right side of the bellows are modeled as springs. In the model, these springs can only bend in a circular way, with midpoint P. This point P lies on the axis of symmetry, and has a variable distance to the right spring d_p. Alpha (α) is half the total bend angle, d_b is the bellows diameter, d is the distance between the Niti springs in rest and the arrows give the positive direction of the forces of the NiTi springs and the bellows

The only variable that can be chosen is d , so we find the d that maximizes the moment:

$$\frac{\partial M_{niti}}{\partial d} = 8k_n d_{maxM} \sin(\alpha_{max}) + k_n \Delta u_0 = 0 \tag{8.6}$$

$$d_{maxM} = -\frac{\Delta u_0}{8\sin(\alpha_{max})} \tag{8.7}$$

Note that this value is only dependant on one property of the NiTi, and the maximum bending angle. The maximum moment now becomes:

$$M_{niti,max} = -\frac{k_n \Delta u_0^2}{16\sin(\alpha_{max}} \tag{8.8}$$

Because in rest there is no net force and moment acting on the device, this moment is counteracted by the bellows. Because in the model, the bellows bend in a circle, the arc-length is used here:

$$\Delta u_b = u_{b,left} - u_{b,right} = 2\alpha_{max} d_b \tag{8.9}$$

$$\Delta F_b = k_b \Delta u_b \tag{8.10}$$

$$M_b = \frac{1}{2} d_b \Delta F_b \tag{8.11}$$

$$M_{b,max} = -M_{niti,max} \tag{8.12}$$

When we rewrite this as a function of k_b we get:

$$-M_{niti,max} = \frac{1}{2} d_b k_b 2\alpha_{max} d_b = d_b^2 \alpha_{max} k_b \tag{8.13}$$

Formulae (8.8) and (8.13) can be combined to give the maximum permissible k_b given the diameter of the bellows d_b:

$$\frac{k_n \Delta u_0^2}{16 \sin(\alpha_{max})} = d_b^2 \alpha_{max} k_{b,max} \tag{8.14}$$

$$k_{b,max} = \frac{k_n \Delta u_0^2}{16 \sin(\alpha_{max}) d_b^2 \alpha_{max}} \tag{8.15}$$

From this is known that when designing the bellows, the spring constant should be smaller than that value. From here a k_b within range is chosen the corresponding forces and distances are calculated. First the distance between the NiTi springs needed is calculated so that with a certain k_b the device is in rest at the maximum bending angle. In other words, the net moment is zero:

$$M_{niti} = d \cdot k_n (4d \sin(\alpha_{max} + \Delta u_0) \tag{8.16}$$

$$M_b = d_b^2 k_b \alpha_{max} \tag{8.17}$$

$$0 = M_{niti} + M_b \tag{8.18}$$

$$0 = (4k_n \sin(\alpha_{max}))d^2 + (k_n \Delta u_0)d + d_b^2 k_b \alpha_{max} \tag{8.19}$$

$$d = \frac{-(k_n \Delta u_0) \pm \sqrt{(k_n \Delta u_0)^2 - 4(4k_n \sin(\alpha_{max}))d_b^2 k_b \alpha_{max}}}{2(4k_n \sin(\alpha_{max}))} \tag{8.20}$$

This gives two solutions. But with a very small d the Niti springs will intervene at a lower bending angle. If the maximum angle is below 40 degrees, then both solutions can be used. But due to other limitations, like that the non-actuated NiTi spring may not be compressed externally; the usable range of the Bellows spring constant is seriously limited. A higher possible bending angle may be needed to be able to reach the 45 degrees rotation under a load. For the remainder the highest value from the two is chosen. With this value of d the moment of the NiTi spring can be calculated. Using Equation (8.3) and Equation (8.16) the force difference and length difference can be calculated as well:

$$M_{niti} = d \cdot k_n(4d \sin(\alpha_{max}) + \Delta u_o) \tag{8.21}$$

$$\Delta F_{niti} = \frac{M_{niti}}{d} \tag{8.22}$$

$$\Delta u_{niti} = u_{niti,left} - u_{niti,right} = 4d \sin(\alpha) \tag{8.23}$$

If the force of the right NiTi spring at the maximum bending angleis chosen to be F_{max} the force at the left NiTi spring can be calculated as well as the lengths of both NiTi springs:

$$F_{niti,right} = F_{max} \tag{8.24}$$

$$F_{niti,left} = F_{max} + \frac{M_{niti}}{d} \tag{8.25}$$

$$u_{niti,left} = \frac{F_{niti,left}}{k_n} + u_{0,cool} \tag{8.26}$$

$$u_{niti,right} = u_{niti,left} - 4dsin(\alpha_{max}) \tag{8.27}$$

With these forces the total force on the bellows can be calculated:

$$F_{bellows} = F_{niti,left} + Fniti, right = 2F_{max} + \frac{M_{niti}}{d} \tag{8.28}$$

The length of the Bellows at the maximum bending point can be calculated as well. Because the length of the right NiTi spring is known and the bending angle is known, the height at the attachment point of the right bellows side can be calculated.

$$h_{b,right} = u_{niti,right} + dh - (\frac{1}{2}d_b - d)2\sin(\alpha_{max}) \tag{8.29}$$

$$dp = \frac{h_{b,right}}{2\sin(\alpha_{max})} = \frac{u_{niti,right} + dh}{2\sin(\alpha_{max})} - (\frac{1}{2}d_b - d) \tag{8.30}$$

$$u_b = 2\alpha_{max}(dp + \frac{1}{2}d_b) \tag{8.31}$$

Now the rest length of the Bellows can be calculated as well:

$$F_b = F_{b,left} + F_{b,right} \tag{8.32}$$

$$F_b = k_b(2u_{0,b} - u_{b,left} - u_{b,right}) = k_b(2u_{0,b} - 2u_b) \tag{8.33}$$

$$u_{o,b} = \frac{F_b}{2k_b} + u_b \tag{8.34}$$

Now only the distance between the NiTi springs and the Bellows needs to be calculated, to be able to check this value against the requirements:

$$d_0 = \frac{u_{niti,right} + dh}{\sin(\alpha_{max})} \cdot \cos(\alpha_{max}) - dp - r_{niti} \tag{8.35}$$

So, with given values for the input parameters α_{max}, d_b, dh and F_{max} for a certain k_b the output parameters can be calculated, which should obey the following restrictions:

k_b	$\in [0, k_{b,max}]$
$F_{niti,left}$	$\in [0, 3]$
$F_{niti,rest}$	$\in [0, 3]$
d	> 0
$u_{0,bellows}$	$\in [1, 20]$

The restrictions on the Bellows length are somewhat arbitrary. It depends entirely on what is possible with the manufacturing means. To see if this design is feasible, some numbers of the properties for the Bellows need to be gathered and compared with the numbers of the model. Using the calculation model above, it is easiest to loop over all possible input variables, and then find the range of all output parameters that satisfy the restrictions. The following method was used:

- With given input variables α_{max},d_b,dh and F_{max} , the maximum permissible k_b was calculated.
- For the range $k_b \in [0, k_{b,max}]$ the output variables are calculated.
- The restrictions are checked
- Return the range for k_b and the corresponding values for $u_{0,bellows}$ that satisfy all restrictions

For now, only the design parameters of the Bellows are examined, so over the ranges $F_{max} \in [0, 3]$ and $dh \in [0, 2]$ is looped to find out what combinations of k_b and $u_{0,bellows}$ are possible, given a certain d_b. In the formulation, k_b can be sampled, so while looping, for a certain value of k_b and d_b the total possible range of $u_{0,bellows}$ can be found.
Figure 8.3 shows the minimum and maximum permissible $u_{0,bellows}$ as height lines.

8.3 Possible Problems

Possible problems for the demonstrator:

- The model used in this case is very simple, and maybe the bellows will not bend as a circular arc. We know it really does not at high angles ($>$ 90 degrees).

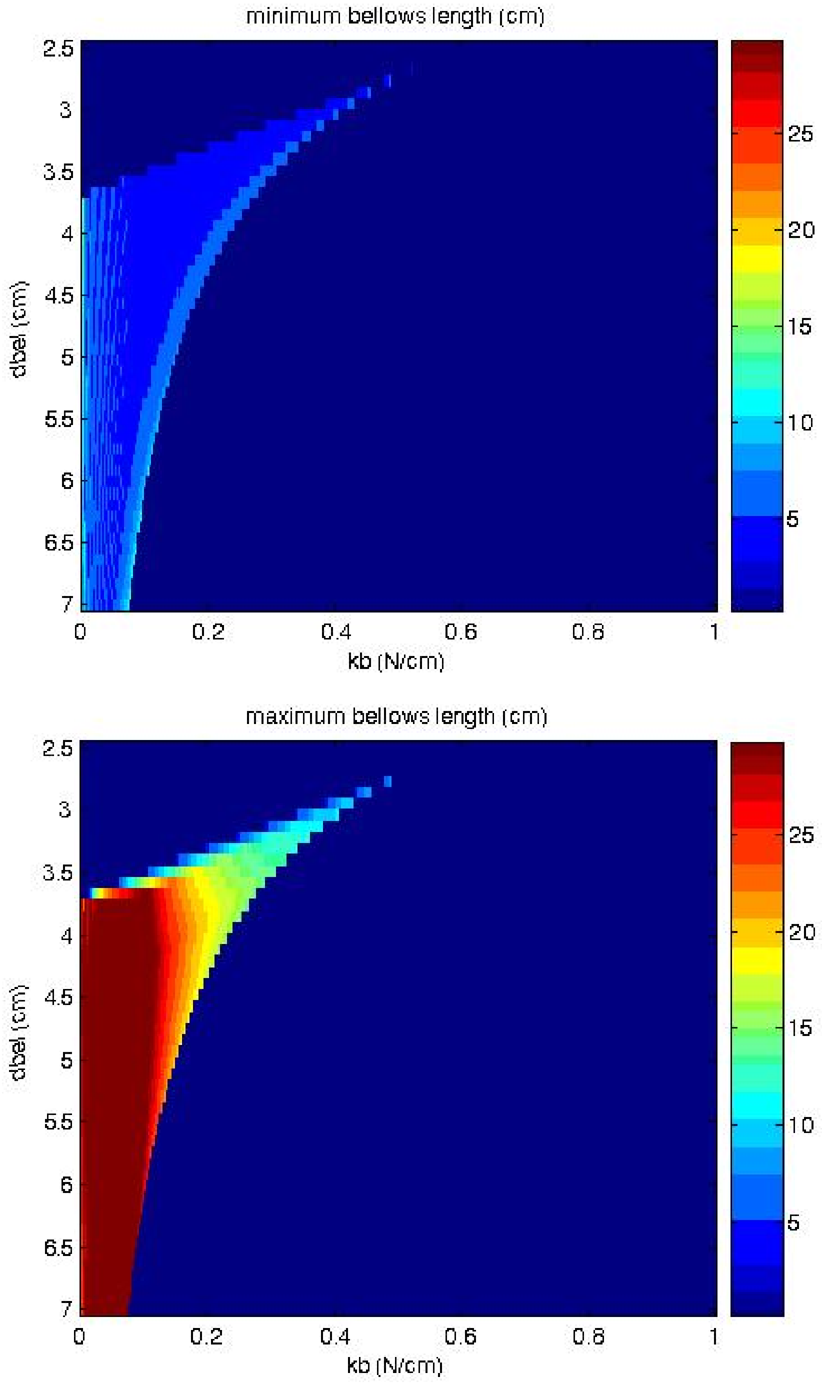

Figure 8.3: Minimum and maximum possible values for the bellows length for given NiTi spring length, as function of the bellows diameter and spring constant. All other parameters can be chosen to satisfy the constraints. As can be seen, the minimum bellows length for this model is around 7 cm.

- We did not take into account that the SMA wire will always have some contraction force left when not actuated. This is because the SMA actuator can only contract by itself, not extend. In this model we just assumed we can control the length, and that no force is exerted when the bending returns to 0.

- Controlling the compression of the spring is probably difficult. Not much literature on that, but we found two articles about precision control [49] [50]. May be a learning system can be used here.

- Attaching the spring (with the eyes at the end) to the flange on the bellows could be difficult. We should buy a variety of shapes for the bellows, to be sure one of that will have the desired parameters as calculated in Figure 8.3.

- Our model now only includes one SMA actuator. When we add a second one on the opposite side which can bend the bellows in the opposite direction, we have to take into account that on bending for instance to the right, the left SMA actuator will be extended a bit. Maybe due to the compression of the bellows that will not be much, but we should add that in the model

- When the second SMA actuator is added, then we have to take into account the residual force of that one as well. That residual force will counteract the compression of the first SMA in the beginning (it is a little bit extended), but as the first SMA compresses, the second may then even help bending as it will counteract the compression force a bit.

Possible future problems for a working application:

- The current system is not robust. If the spring breaks down, no active control is possible and the desired end-effector position may no be reached. Many connected segments should overcome that problem. Using multiple micro helices can overcome this problem, as one malfunctioning helix should be no problem

- The whole setup as described above may not be stiff enough, and may have a slowly decaying oscillation on external exerted forces

- The bellows may be too weak for offsets, which means that if a load is being carried perpendicular to the axis, the bellows will look like the next figure. Compensation springs could overcome that problem.

- Many compensation springs could be necessary, which makes the bellows-system more stiff from the NiTi spring viewpoint. Will there be enough force?

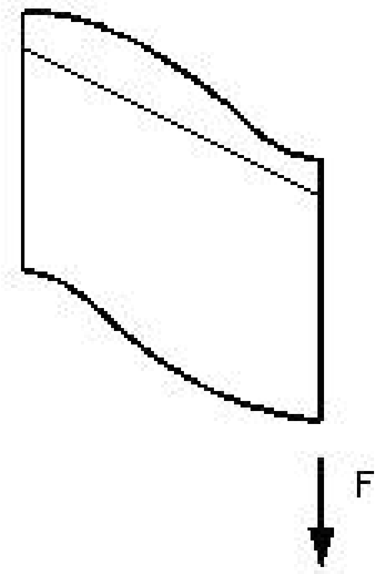

Figure 8.4: bellows

- If the current demo-setup is used in the robot arm like this, we miss a vital rotation to position the end-effector.
- Getting maximum working range. The model didn't include a stiffness matrix.

Chapter 9

Prototype & Testing

Since bellows with the right dimensions are not commercially available, a spring with the same properties besides that it is not torsion stiff, is used for the prototype. During experiments the prototype should not be tested on torsion.

9.1 Experimental demonstrator

An experimental demonstrator joint was built using 18 components (6 SMA connectors, 3 SMAs, 4 discs, 1 outer spring, 2 screws, 2 bolts). Initially bellows were selected to serve as an exoskeleton. However, these could not be fabricated within the budget. Therefore a compression spring was used as an outer spring instead. A 3D CAD representation is depicted in Figure 9.1.

Figure 9.1: The prototype consist of three NiTi springs inside an exoskeleton, made of a spring with very low stiffness. The two covers can adjust the distance between the NiTi springs. Heating one of the NiTi springs by applying a voltage will shorten the NiTi spring and a rotation will follow

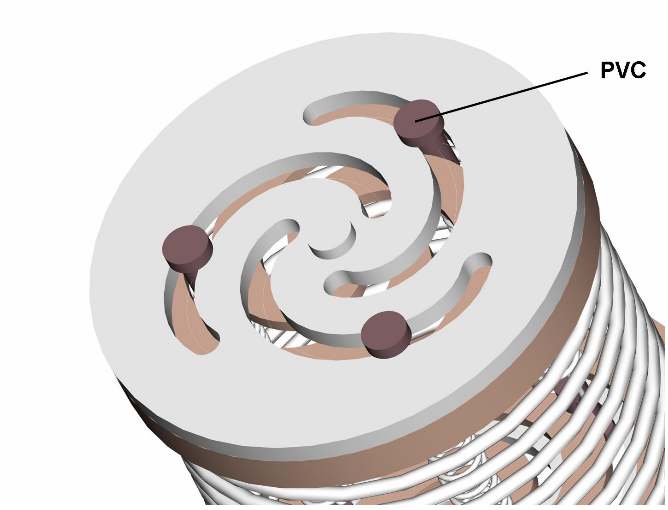

Figure 9.2: The mechanisms of the prototype for adjusting the distance between the NiTi springs

Heating of the SMAs was done by applying a current of 1.5A. To prevent short circuitry the SMA connectors were made from PVC so that the SMAs were electrically separated from each other. With the three SMAs movement in two directions can be realized.

At both ends of the spring two spiral grooved plates (counter clockwise and clockwise) were mounted. The SMA attachment pins were placed trough the intersection points of the two spiral grooves. By moving the plates in the opposite direction of each other, the intersection point moved along with the SMA attachment points. This mechanism supplied an adjustment of the place where the SMAs are attached with respect to the center.

A movie strip of the demonstrator set up in action is given in Figure 9.2, with a 4 seconds frame interval.

9.2 Measurements and results

The experimental demonstrator was measured on its performance. Only the bending angle was measured using a background with degree-marking. To prevent parallax effects, a video camera was used which fixed the viewpoint. Measurements were done for 3 different outer springs (zero length and stiffness) and different settings of the SMA-position (SMA diameter). For the given settings, the results of the experimental demonstrator were

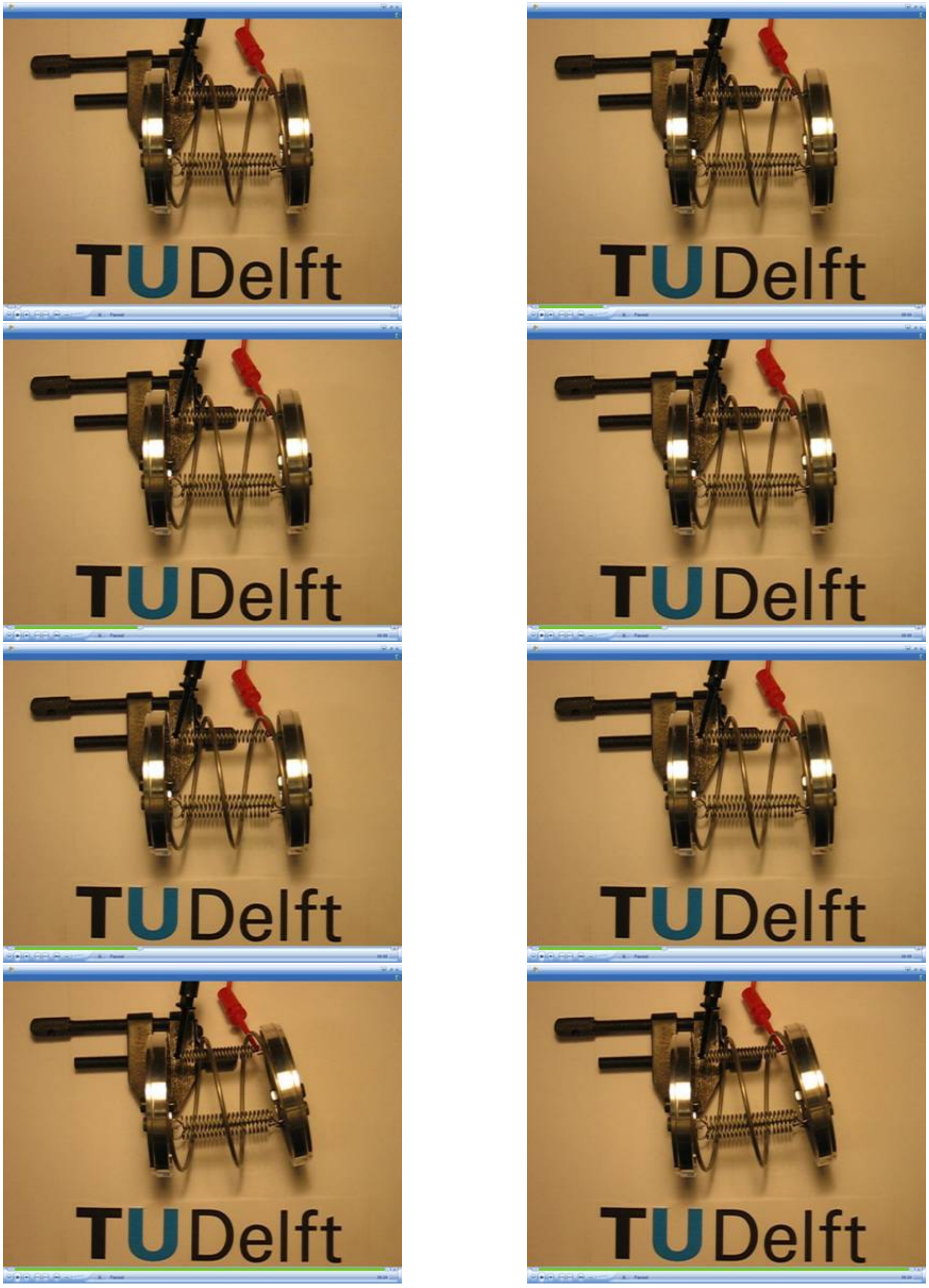

Figure 9.3: Experimental demonstrator

better than could be predicted with the simulation model. Bending angles of 10 degrees (thus a workspace of 20 degrees) were obtained. However, the theoretical 75 degrees was not realized. The effect of using a stiffer outer spring resulted is a slightly lower workspace, but a larger joint stiffness and stability.

During the experiments the SMAs got so hot they melted the PVC attachment pins. This can easily be prevented by making the discs of PVC and the attachment pins of metal.

Chapter 10

Conclusions & Recommendations

Biology provides us with numerous examples of beautiful mechanisms. In the report 34 mechanisms were identified and described, of which 15 mechanisms on kinematic level, 11 mechanisms on actuating level, and 8 mechanisms on control level. In short it was found that:

1. hydroskeletons have different muscle arrangements that enable different types of motion without a structural skeleton at all,
2. exoskeletons have asymmetric joint activation (sometimes even based on hydraulic principles) with return spring mechanisms,
3. exoskeletons have a closed skeletal structure that flexes on the point where joints are required (so there are no sliding elements),
4. endoskeletons have clever mechanisms that facilitate a.o., energy storage, weight compensation, and muscle translocation, most of them serve dynamic movements,
5. mammals have a highly developed neuro-musculo-skeletal systems that enables optimal and adaptive control.

Combining these findings brought us an idea for a spring mechanism that can change shape, performing the function of a joint. The principle consists of pre-tensioned springs (agonist-antagonist pairs) of which the agonist is an actuator, and the antagonist is the carrying and enclosing structure (exoskeleton) of the joint. This way a joint without sliding elements can be constructed which reduces energy dissipation, and the need for bearings or lubrication. It is proposed to use Shape Memory Alloy actuators to obtain a simple and compact mechanism.

Biological passive mechanisms have muscle stretch of 40% whereas NiTi SMA actuators have a typical stretch of 6%. When NiTi SMA wires are applied as muscles the stretch is too small. Therefore Helical shaped SMAs (from Toki Corporation) were used that have a stretch of 100-200%. Since very few is known of these specific actuators, measurements were done. It was shown that the stiffness of these actuators is fairly constant for different loads and temperatures. However, rest length is not constant but depends non-linearly on the load applied. Also there is a fair amount of hysteresis present. This makes modeling and motion control of SMAs difficult.

The joint mechanism requires the exoskeleton structure to have specific mechanical properties that determine the joint stiffness and movement workspace. The degree(s) of freedom that allow motion should be low in stiffness to allow motion. However, they should also provide a pre-loading force to apply a pre-tension to the SMAs. So there is an optimal stiffness for the exoskeleton structure. A simple simulation model was built and showed that with optimal mechanical properties of the exoskeleton structure a workspace of 75 degrees could be achieved. However, a structure that is able to bend in such a range and meets the stability requirements of the other degrees of freedom was not found. We expect that structures similar to bellows might meet the requirements.

An experimental demonstrator of the new joint concept was build and proved that the concept worked. As an outer structure we used a compression spring. Bending angles of 10 degrees (thus a workspace of 20 degrees) were obtained. However, the theoretical 75 degrees was not realized. The demonstrator also had some short comings. First, the PVC attachment pins melted due to the heat generated by the SMAs. For future prototypes it is recommended to use metal attachment pins and for instance electrically isolating end caps to prevent short circuitry. Another point of care is the assembly. The SMAs were attached to their attachment pins by manipulating instruments between the windings of the outer spring. If a closed outer structure would be applied (e.g. bellows), assembly of this system becomes impossible and another design is required.

For the experimental demonstrator, commercially available helix SMAs were used. The available product arrangement of helix SMAs is very small. So the SMAs applied are far from optimal. More powerful SMAs would improve the performance of the demonstrator and its usability, for instance by increasing the SMA wire diameter. Another option is to investigate whether more biologically inspired muscle arrangements are possible with SMA wires, e.g. penate muscle arrangements in stead of helix shapes.

In conclusion, many problems remain still to be solved such as how to design an exoskeleton structure, modeling and optimization of the joint, controllability of the joint, and how to deal with space requirements. All these issues will also depend on a final application. For instance the joint concept proposed is more applicable when the torque requirements are low, but the adaptation to the environment is important (e.g. a spectrometer that needs to be compressed to a rock with a certain force), than for applications where the torque requirements and precision are high (e.g. positioning a robot arm). Nevertheless, by looking at biology we have shown that we can come up with a new articulation concept inspired by nature.

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