DISSERTATION / DOCTORAL THESIS

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„The Flexibility Trainer:

Biomechanical analysis of martial arts kick performances for user centred product development"

verfasst von / submitted by

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Sincerely,

Dominik Hoelbling

Contents

I. Introduction

Sport device development for the improvement of sport specific, complex physical abilities, poses considerable challenges to experts in the fields of biomechanics and engineering as it requires in-depth understanding of the underlying pre-requisites in the respective sport. Particularly fast sport movements such as Martial Arts kicks, depending on a variety of anatomical, physiological, mechanical, and tactical aspects are difficult to analyse. Therefore, they require simplified models to gain in-depth understanding of essential movement patterns for successful execution. This includes a challenging compromise between the complexity of the movement and the desired relative simplicity of a model. In particular, the model must be sufficiently complex to reflect all the significant locomotion fixtures but clear and simple enough to allow understanding and application. Furthermore, the resulting knowledge should be translated into state-of-the-art training methods and effective sport engineering development.

The study aims to gain comprehensive understanding of the biomechanics of the double side kick and implement the knowledge in the design of a sport-specific device for improvements of kicking movements in striking Martial Arts, such as Kickboxing, Karate, Taekwondo, MMA, Muay Thai, Kung Fu and others. The efficacy of such a device can only be assessed by indexes that measure appropriate physical attributes critical to superior performance. Summarised, this can be expressed in the overall research question: How can Martial Arts kick performances and their physical pre-requisites be analysed, and outcomes translated into the development of a novel sports device?

To fully understand the approach of this dissertation a number of explanations and theoretical fundamentals are explained in the following introduction chapter. They comprise an excerpt of Martial Arts (from their history to current rules and regulations), as well as selected fundamentals of biomechanics, physiology, analysis methods, and sports device engineering and market summary.

1. Martial Arts

Martial Arts are "codified systems and traditions of combat practiced for a number of reasons such as self-defence; military and law enforcement applications; competition; physical, mental and spiritual development; and entertainment or the preservation of a nation's intangible cultural heritage" (Spruiell, 2005).

There are many different forms of Martial Arts, that are generally classified into six different classes based on their main field of technique operations (BxRank, 2015):

(1) Striking or stand-up styles (e.g. boxing, karate, and kickboxing), which predominantly use kicking and punching techniques.

(2) Grappling or ground fighting styles (e.g. brazilian jiu jitsu, sambo and wrestling), which focus on holding and locking techniques to restrict the opponents' movability.

(3) Throwing or takedown styles (e.g. Aikido, Hapkido and Judo), where fighters start in a stand-up position and the main goal is to throw the opponent to the floor.

(4) Hybrid sports styles (e.g. Kung Fu and MMA), which include elements of all the above styles.

(5) Weapons based styles (e.g. Fencing, Iaido and Kendo), which focus on weapon fighting.

(6) Meditative and low- to non-impact styles (e.g. Chi Gong, Tai Chi, Kata and Forms), which consist of specific movement tasks, often in combination with breath timing.

All these styles originally descent from war training of different epochs and areas.

1.1Excerpt of Martial Arts history

Martial Arts or fighting arts historically evolved as systematic approaches to prepare for war or defence actions. As such they are considered to be nearly as old as humankind itself and have emerged from different animal hunting to human vs. human styles. Cave paintings of fighting actions or combat operations were found dated back to stone age (Hamblin, 2006, p. 15). More advanced early forms of competitive wrestling were known in India (Green, 2001, p. 787) and ancient Egypt in about 3000 B.C. (Britannica, 2020). In the far east, the earliest ancient records date back to about 2600 B.C. from China named 'heroism in fist fighting' (Gärtner, 2013, p. 20) and a section of Veda from India about 1700 B.C. (Cush, Robinson, & York, 2012, p. 182). Later, ancient Greeks even included wrestling and fist fighting into the Olympic games from 776 B.C. (Britannica, 2020). Meanwhile, Sun Zi wrote *The Art of War* in China (511 B.C.). From that time on Asian Martial Arts were constantly evolving, changing, and spreading to different regions.

In Europe, however, after the gladiator fights in the roman empire starting at 264 B.C. (Mann, 2013, p. 16) further recorded milestones in Martial Arts were found in the middle ages in poems (e.g. from Johannes Liechtenauer) and fighting instructions (Tobler, 2010). The oldest current Martial Arts codes, such as judo and karate in Asia, as well as boxing and fencing in Europe were developed in the 19th century (Green, 2001, pp. 817-822). Specific milestones for the development of these Martial Arts were for example the records of Judo, implemented in Japanese police training 1871 (Green, 2001, p. 821) and the introduction of *Shôrin-ryû* Karate in Okinawan public schools. For European sports, the records of modern fencing were found in the publication *Schools and Masters of Fence* from 1884 and new rules for amateur boxing were published from the Marquis of Queensberry in 1867 (Green, 2001, p. 822).
Since the late 19th and early 20th century most Martial Arts underwent another significant change. From a form of art or war to a sport. Very specific rules and codes have been implemented, with referees executing them and even new sports have been formed to compare fighters from different Martial Arts to each other (e.g. Sports Karate and Kickboxing). In Europe many Martial Artists refer to it as *Americanisation* (Gärtner, 2013, p. 22) of Martial Arts. In combination with the usage of newly introduced safety equipment, like boxing gloves, head, and foot protectors as well as categories based on weight, sex, and age, Martial Arts became mainstream. Unfortunately, this process did not only contribute to the codification of different sports but also to the formation of different federations within the sports (e.g. in professional boxing or amateur kickboxing), which is widely believed to be critical and counterproductive for development, evolution, and commercialisation of sports. Therefore, this study only includes fighters, performing at least one IOC (International Olympic Committee) recognized sports discipline (IOC, 2020).

1.2 Sport Martial Arts

This work focuses on Martial Arts as sport disciplines, particularly, striking, or stand-up Martial Arts (see chapter 1: Martial Arts). However, there are further ways to classify these disciplines, in order to get a more precise orientation and to narrow the topic. First and foremost, sport codes allow different techniques, for example hand (e.g. boxing) and foot

(WT[1] taekwondo) techniques or both (e.g. kickboxing, karate, Sports Karate, savate, muay thai and ITF taekwondo).

Furthermore, general types of Martial Arts, based on their direct origin (e.g. traditional and modern) can be distinguished.

Traditional disciplines (e.g. WKF[1] karate) are characterized by the inclusion of rules describing the kinematic and behavioural aspects of technique execution of allowed techniques. In example the *World Karate Federation* only awards points if the following criteria are met: “a) Good form, b) Sporting attitude, c) Vigorous application, d) Awareness (ZANSHIN), e) Good timing, f) Correct distance” (WKF, 2020).

Modern disciplines (e.g. WAKO[1] kickboxing), however, tend to avoid most subjective terms and focus on very general technique description and exclusion criteria, such as described in *Art. 3 Legal Techniques* and *Art. 4 Illegal Techniques and Actions* of WAKO[1] (WAKO, 2020b).

Another general distinction can be based on the respective scoring system of the disciplines. In *Running Time (or Continuous)* disciplines (e.g. WAKO[1] light and full contact kickboxing or Muay Thai), the fight is held continuously during the bout time unless a rule violation or technical difficulty occurs.

Pointfighting (e.g. WAKO[1] Pointfighting kickboxing, WKF[1] karate or ISKA[1] Sports Karate) on the other hand, is characterized by the ’Point-Stop‘ scoring system, where only the first regular technique which reaches the opponent scores as a point and leads to a short point awarding break.

In summary, the methodical approach of this research predominantly focuses on modern striking Martial Arts, which include kicking technique, and are performed as Pointfighting disciplines. As the codes of the considered disciplines (Pointfighting kickboxing and Sports Karate) constitute that (a) a very high level of technique quality is necessary for successful execution (because only the first target contact scores) and (b) less boundary conditions (compared to traditional codes) lead to higher variety of execution patterns, render them ideal to extract significant movement patterns.

[1] An abbreviation in capital letters prior to a sports discipline refers to a sports federation, such as UFC for Ultimate Fighting Council, WT for World Taekwondo, ITF for International Taekwondo Federation, WAKO for World Association of Kickboxing Organizations, WKF for World Karate Federation, ISKA for International Sports Karate Association, NASKA for North American Sports Karate Association, AIBA for Amateur Boxing Association, WBA for World Boxing Association and WBC for World Boxing Council.

1.3Modern Pointfighting Martial Arts

The modern Pointfighting disciplines such as ISKA[1] Sports Karate Point Sparring and WAKO[1] Pointfighting kickboxing emerged from traditional karate in the 1970s and 1980s (ISKA, 2020a; WAKO, 2020a) in order to provide a platform to compare different Martial Artists within a new set of rules. However, due to the sports' rising popularity, they became more and more independent from their traditional roots. These particular federations were chosen as they represent the largest and most recognized Pointfighting disciplines, according to participation numbers of their biggest tournaments (ISKA, 2020b; Soportdata, 2020).

WAKO[1] Pointfighting kickboxing (formerly semi contact), differs to ISKA[1] Sports Karate only in numeric score for specific techniques, few general rules and bout times.

Table 1: Rule differences between federations retrieved from NASKA (2020) and WAKO (2020b)

	WAKO Pointfighting kickboxing	ISKA Sports Karate
Points award:		
Hand techniques		
Head	1 point	1 point
Body	1 point	1 point
Foot Techniques		
Head	2 points	2 points
Body	1 point	2 points
Sweep	1 point	1 point
Jumping kick to head	3 points	2 points
Jumping kick to body	2 points	2 points
Jumping, spinning kick to head	3 points	3 points
Jumping, spinning kick to body	2 points	2 points
Bout durations:		
Bout duration at world championships	3 rounds of 2 min. (1 min. break)	1 round of 2 min.
Bout duration at other tournaments	Depending on organizer	Depending on organizer
Excerpt of main general rule differences:		
Touch the ground during or after technique	Not allowed	Allowed
Technical Knock Out (KO)	10 points difference	7 points difference
Win	Most points	Min. 2 points difference
Draw rule	1 min. extra time/ next point	Next point

Code differences, described in Table 1 maybe not particularly significant, however the restrictions regarding bout time and kick point awarding's could provide a larger range of movement patterns, which is generally preferable for the current approach.

2. Excerpt of fundamental concepts in the field

As stated in section I Introduction, successful development of sport devices for the improvement of specific abilities, requires comprehensive understanding of human anatomy in conjunction with fundamental principles of physiology, as the basis of tissue function and adaption and biomechanics as the doctrine of movement and forces. Particularly, these principles must be applied to the design of a device in order to estimate physical strain and predict adaption patterns in interrelation with training science and sports exercise physiology.

2.1 Related physiology topics

Physiology is the scientific discipline that deals with the processes or functions of living organisms, or the study of body functions. It allows us to understand and predict systems' responses to stimuli, as well as understand how the body maintains conditions within a narrow range of values in the presence of a continually changing environment (Tate, 2011). This includes the structure of active and passive elements responsible for human motion. As a basis for a mechanical description of global movements in context of sportive adaptions of bones and muscles are essential. Functions of other tissues, such as cartilage, joint fluids or other connective tissues are of secondary importance in the assessment of healthy participants' complex sport movement patterns.

2.1.1 Skeletal system

The adult human skeleton consists of 206 bones (Haywood, 2008, p. 5). The number of joints, however, differs between 150 and 350 joints, mostly depending on the definition of a joint. The skeletal system is the internal framework of the human body (Culler, 2015) and consists of hard tissues, i.e. bones, and passive soft tissues - cartilage, tendons and ligaments. Bone as the main tissue of the human skeleton "is a vascular connective tissue consisting of cells and calcified intercellular matrix of organic and inorganic substances. Matrix is made up of collagen" (Marjit, 2016, p. 2.27). They are connected with each other via variety of joints passively supported by ligaments and actively adjacent muscles. Voluntary movement of this supporting construction is mainly conducted by muscle contractions initiating a pulling force on tendons connecting the muscle with two or more bones linked by one or more joints.

2.1.2 Muscular system

"Muscle is a type of tissue, composed of contractile cells or fibres, which effects movement of an organ or body. The outstanding characteristic of muscular tissue is its ability to shorten or contract" (Thomas, 1981). Skeletal muscles as one of the three major types are the most important tissues in sport motion analysis, as their contraction generate voluntary movements. In conjunction with the skeleton they form the musculoskeletal system, whose kinematic patterns are the subject or biomechanics in general and motion analysis in particular.

The skeletal muscle is made of numerous muscle fibres, each formed of several hundreds of myofibrils. The contractile protein elements within myofibrils are called actin and myosin (see Figure 1).

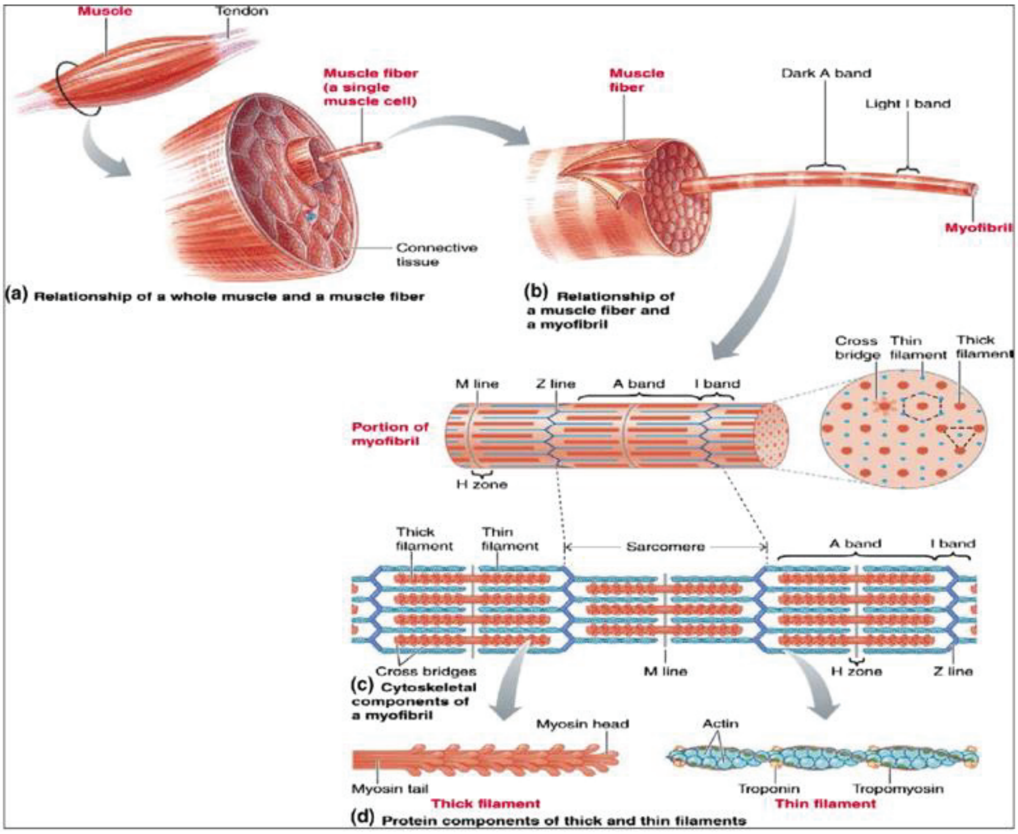

Figure 1: Structure of skeletal muscle (Sherwood & Learning, 2010).

As visualised in Figure 1 myosin filaments have little golf cup-like heads, which, connect with and compress the actin filaments when contracted, which produces a force and if not counteracted, shortens the muscle.
Furthermore, there are different types of muscle contractions, determined by the movement direction during the contraction.

2.1.2.1 Concentric contraction

The concentric contraction describes an exercise where the movement direction, during the contraction results in muscle shortening (see, Figure 2A).

2.1.2.2 Isometric contraction

A muscle is isometrically contracted, when the respective segments do not move during contraction, i.e. the muscle retains constant length while generating force (see, Figure 2B).

2.1.2.3 Eccentric contraction

The eccentric contraction describes an exercise where the movement direction, during the contraction results in muscle lengthening (see, Figure 2C).

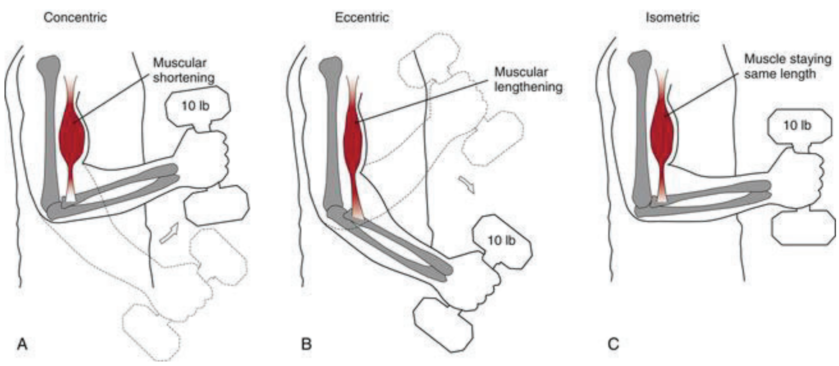

Figure 2: Types of contraction (Campolo, 2015).

2.1.2.4 Antagonistic muscle action

Another important aspect of movement is muscular extension of the antagonistic muscle. This is not only determined by muscle length but on large scale by the central nerval innervation.

2.1.3 Nervous system

The *nervous system* is divided into *central* and *peripheral nervous system*. The *central nervous system* comprises the *brain* and the *spinal cord*, whereas the *peripheral nervous system* consists of the *spinal nerves* and the *autonomic nervous system*. Latter is the route of both, the *sympathetic* and *parasympathetic system* (see Figure 3).

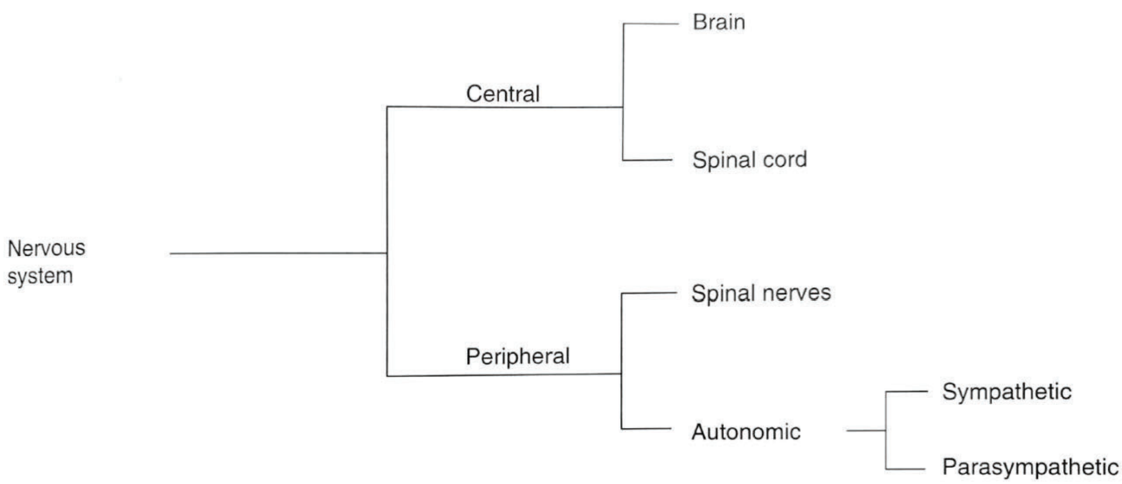

Figure 3: Structure of the nervous system (Alter, 2004, p. 85).

Skeletal muscles possess a basic *muscle tone* controlled by the *sympathetic* part of the *autonomic peripheral nervous system*. The *muscle tone* or *residual muscle tension* is the continuous and passive contraction of a muscle, or the resistance to a stretch stimulus in resting state (O'Sullivan, Schmitz, & Fulk, 2007). Its general propose is to prevent the supporting structures of the body from collapsing. For movement however, the antagonistic muscle tone is reduced in order to allow the agonistic muscle to initiate the motion. On the other hand, this passive muscle tone is increased, when the muscle is stretched, especially after the length of usual movement range in order to prevent damage due to unsupported actions. The sensory element for this central nerval induced muscular feature is called muscle spindle (Alter, 2004, p. 89). It is a sensory nerve, which spins around muscle fibres and their “primary endings measure length plus velocity of stretch” (Alter, 2004, p. 90) and then signals the measurements to the sensory neuron within the spinal cord and further to the brain (Figure 4). Unfortunately, this muscular reflex also prevents sportive maximum range movements, if not trained properly. Especially, in adult Martial Artists this often becomes a problem as movement range and its trainability naturally decreases with age (Roaas & Andersson, 1982).

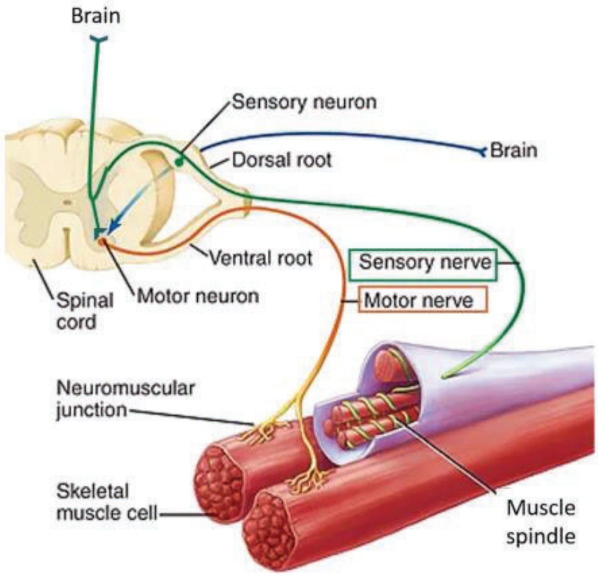

Figure 4: Schematic display of muscle spindle on a muscle fibre (Anatomyqa, 2020).

Another sensory organ indirectly effecting the muscle tone is called Golgi tendon organ (see, Figure 5). It is “a small receptor, located in the junction between a muscle and a tendon, that monitors tension (…) The organ is activated by muscular contractions that stretches the tendon. This results in an inhibition of alpha motor neurons (special neurons that innervate the contractile elements of striated muscle), causing the contraction muscle to relax” (Kent, 2006, p. 237).

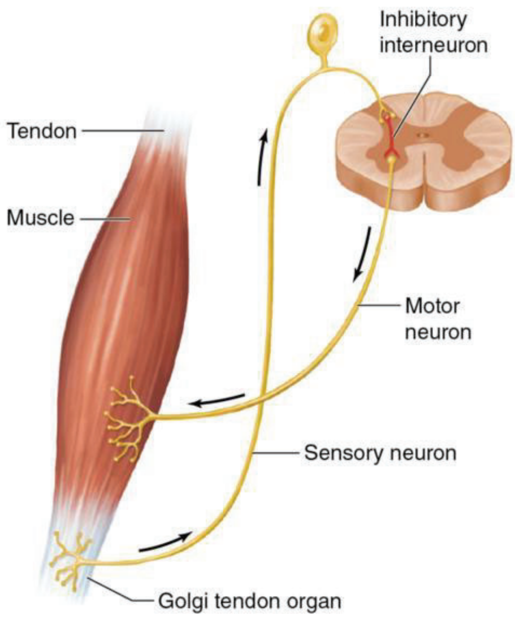

Figure 5: Visualisation of Golgi tendon organ and its interaction with the muscle (Kinetics, 2020).

The described interaction between the Golgi tendon organ and the motor neuron serves as a form of muscle protection. When the muscle contraction (most likely against an external force and combined with the muscle spindle reflex) gets too high, the Golgi tendon organ reacts and forces the muscle to relax, in order to prevent damage. That feature is also called deep tendon reflex. There are other reflexes, which are particularly important to this study, called autogenic and reciprocal inhibition.

2.1.3.1 Autogenic inhibition

Autogenic inhibition (or inverse myotatic reflex) describes a ”reflex inhibition of a motor unit in response to excessive tension in the muscle fibres it supplies” (Kent, 2006, p. 62), meaning that after a maximum contraction a muscle is forced to relax or in other words, lower its’ tension. That is “attributed to the increased inhibitory input arising from Golgi tendon organs (GTOs) within the same muscle” (Sharman, Cresswell, & Riek, 2006). This is of particular importance for (section 5.4.1) Proprioceptive neuromuscular facilitation (PNF) training methods.

2.1.3.2 Reciprocal inhibition

On the other hand, reciprocal inhibition is “a process that inhibits the stretch reflex in antagonistic pairs of muscles. When one muscle contracts it sends inhibitory nerve impulses to its opposing muscle causing it to relax” (Kent, 2006, p. 458). This is used as methodical approach, in a special form of (section 5.4.1) Proprioceptive neuromuscular facilitation (PNF), called (section 5.4.1.2) CRAC training.

2.1.3.3 Stress tolerance/ Stress relaxation

Another important factor associated with the increase in flexibility after training is a lower level of excitability or higher tolerance of stress of the muscle, shown by the H-reflex[2] response test (Sharman et al., 2006).

2.1.3.4 The Gate Control Theory

The gate control theory describes the situation when two kinds of stimuli, such as pain and pressure, activate their respective receptors at the same time (Mazzullo, 1978). In example, the theory states that pressure sensory elements are transferring faster to the spines as peripheral pain receptors, due to their neuronal structure (Hindle, Whitcomb, Briggs, & Hong, 2012). This leads to a higher stress tolerance after muscle contraction.

2.2 Functional anatomy for Martial Arts kicks

As a form of simplification, most biomechanical analysis focus on just 3 elements joints (articulatio or art.), bones (os) and muscles (musculus or m.) Based on kicking movements observations in Martial Arts, the knee, and hip joints of both legs and thus the pelvis (ossa coxae), femurs (os femoris), tibias (os tibia) and fibulas (os fibula) seem to be most significant. Other segments (feet, thorax, arms, and head) fulfil a contributing or if falsely activated a contradicting mechanical function to the movement goals. Therefore, latter will be included into considerations for power development and transmission but are just of secondary importance in this research.

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[2] The Hoffman-reflex "is an artificially induced reflex brought about by electrically stimulating a mixed peripheral nerve" (Sharman et al., 2006).

2.2.1 Hip Joint (articulatio coxae) muscles

For in-depth understanding of sports movements, knowledge on functional anatomy is essential. Particularly complex techniques like Martial Arts kicks depend on interactions of a variety of muscles. Thereby, the hip joint muscles seem to be most significant for the initiation of such movements, as the combination of high abduction, flexion and external rotation is disproportionately more difficult compared to the knee extension. A description of movement directions, neutral positions and Vicon® motion capturing definitions for the hip and knee joint is illustrated in Figure 6.

Hip angles	Flexion (x)	Leg elevation angle on the sagittal plane
	Abduction (y)	Leg elevation angle on the coronal plane
	External rotation (z)	Leg external rotation;
		hip joint centres are defined between calculated pelvis axis and the calculated femur axis, which ends in the knee joint centre
Knee angle	Flexion (x)	Lower leg elevation on the sagittal plane;
		the knee joint centre is calculated using a modified chord function and the hip joint centre with knee and thigh (THI) marker

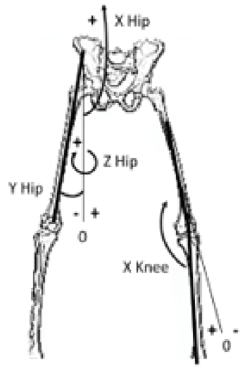

Figure 6: Description and illustration of movement directions, neutral positions and motion capturing definitions for the hip and knee joint.

Main agonists are mentioned in Table 2 for the kicking leg. Furthermore, Figure 7 illustrates a schematic visualisation of the hip joint muscles of the kicking leg during the chambering phase (see, section 7 Technique selection (double side kick)) of a kick.

Table 2: Active hip joint muscles for leg elevation brackets describe muscle position in Figure 7 (Platzer, 2009, pp. 234-246)

Flexion	Abduction	External rotation
M. psoas major (1)	M. glutaeus medius (12)	M. glutaeus maximus (9)
M. iliacus (2)	M. tensor fasciae latae (16)	M. quadratus femoris (13)
(Together M. iliopsoas)	M. glutaeus maximus (9)	M. glutaeus medius (12)
M. tensor fasciae latae (16)	M. glutaeus minimus (11)	M. glutaeus minimus (11)
M. pectineus (8)	M. piriformis (10)	M. iliopsoas (1 & 2)
M. adductor longus (7)	M. obturatorius internus (14)	M. obturatorius externus (15)
M. adductor brevis (7)		All functional adductors (not displayed)
(together with m. gracilis)		M. piriformis (10)
M. gracilis (7)		M. sartorius (not displayed)
(together with M. adductor brevis)		
M. rectus femoris (3)		
M. sartorius (not displayed)		

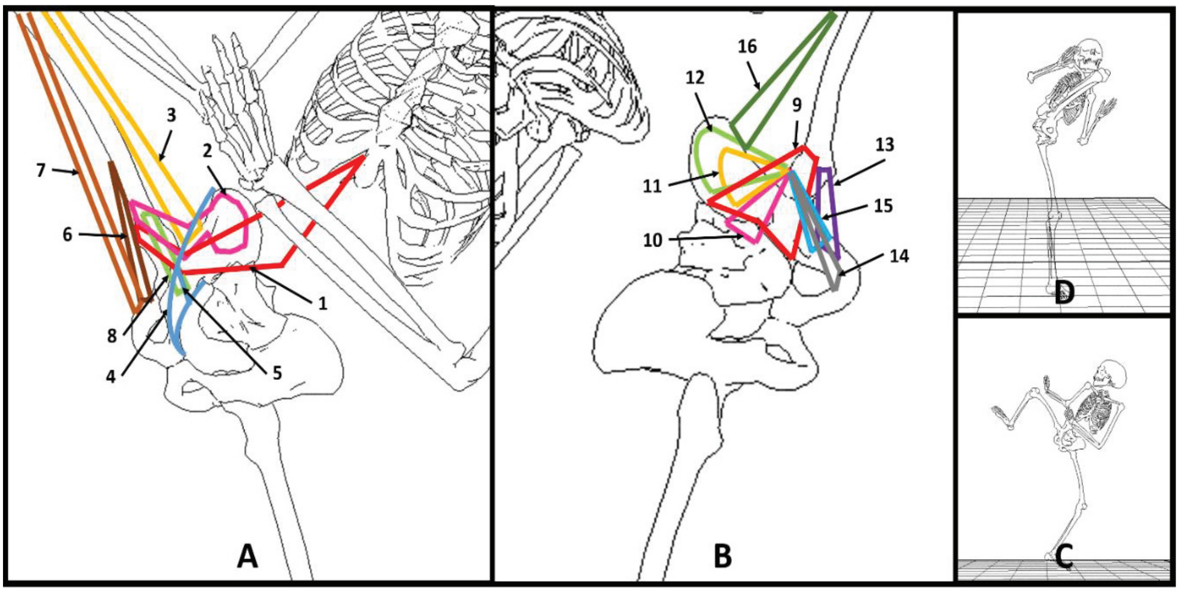

Figure 7: Schematic illustration of active hip joint muscles during leg elevation. Muscle designations in Table 2 (Hoelbling, 2016a)

The supporting leg action is believed to use the same set of muscles as the kicking leg, but in a different sequence of tensions and contractions.

Besides the agonists, there are several muscles directly or indirectly inhibiting the technique with regard to the movement goal. These antagonists include the adductors (m. adductor longus, -magnus and -minimus) as well as the ischiocoral muscles (m. biezeps femoris, m. semitendinosus und m. semimembranosus). It is noted that these muscles, thus contradicting the leg elevation, still serve a very important purpose, namely joint stabilization. The simplified schematic illustration in Figure 8 outlines the position and tthe mechanical properties of these muscles.

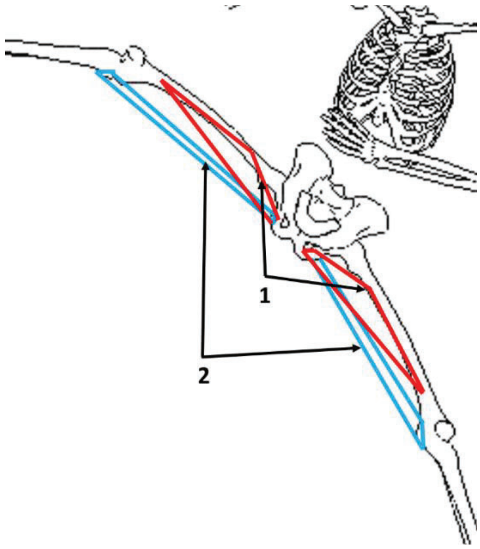

Figure 8: Simplified schematic illustration of the adductors (1) and ischicoral muscles (2) (Hoelbling, 2016a).

2.2.2 Knee joint (articulatio genus) muscles

The second main movement type of the kick is the knee flexion and extension. In comparison to the leg elevation it is easier to conduct as it is an essential part of everyday live. Knee flexion is primarily conducted by the m. biceps femoris, however m. semitendinosus and m. semimembranosus might be co-active (Platzer, 2009, pp. 251-253). Knee extension is conducted by m. quadrizeps femoris, consisting of m. rectus femoris, m. vastus intermedius, m. vastus medialis and m. vastus lateralis, with a coactivation of m. sartorius (Platzer, 2009, pp. 248-250). It is notable that the three joint flexors caput longum of m. biceps femoris, m. semitendinosus and semimembranosus are often limiting the full extension of the kick or forcing the leg to a lower position for extension.

2.3 Related biomechanic concepts

"Mechanics is the study of the effect that physical forces have on objects" (Rao, 2006, p. 1), which means that "Biomechanics is the science that examines forces acting upon and within a biological structure and effects produced by such forces" (Nigg & Herzog, 1994, p. 2). Biomechanics include numerous sub-areas, such as kinetics, kinematics, direct dynamics, inverse dynamics, balance, and stability. All these areas are also used in sports biomechanics, which is defined as "the science of mechanical description and explanation of phenomena and causes in movement and sport on the foundation of the human organism" (Roth & Willimczik, 1999). Generally, it can be stated that sport biomechanic analysis is a systematic simplification, i.e. models based on fundamental laws, axioms, principles and built on concepts (Nigg & Herzog, 1994, pp. 369-370).

2.3.1 Selected fields of biomechanics

2.3.1.1 Kinematic

Kinematic is "the study of the geometry of motion" (Nigg & Herzog, 1994, p. 254) and is the foundation of the most complex technique analyses and descriptions. Optical methods, like 2D and 3D motion capturing systems such as Kinovea (Charmant, 2004) or Vicon® (Vicon®, 1979) are widely used to detect and define movement patterns in sports.

2.3.1.2 Dynamic

"Dynamics is the particular branch of mechanics that deals with the study of the effect that forces have on the motion of objects" (Rao, 2006, p. 1) and can be divided into direct and inverse dynamics. Direct dynamics is the "mechanical analysis of a system that starts with force and determines a movement", whereas inverse dynamics "starts with the movement and determines force" (Nigg & Herzog, 1994, p. 36). It is usually a combination of both methods, which enables a researcher to evaluate complex systems accurately and comprehensively.

2.3.1.3 Balance and Stability

Balance can be defined as the equilibrium of a body, whereas dynamic balance refers to the "body equilibrium in motion" (Arus, 2012, p. 19) and static balance describes conditions in which external- with internal forces are compensated (Arus, 2012, p. 94). Stability on the other hand refers to the ability of a body to restore balance. Therefore, it is stated that stability in human movement can be quantitatively indicated by the distance between the centre of pressure and the centre of mass (if the supporting area is similar), whereas balance can be described as the distance between the centre of pressure and solely the horizontal position of the centre of mass.

2.3.2 Selected fundamentals of mechanics

For complex motion analysis, it is necessary to derive motion equations for the moving body segment. As the number of measurements is naturally limited, biomechanists use basic principles of physics and mechanics to calculate missing variables. These principles must be well understood and carefully applied to avoid errors. The following part consists of selected fundamentals relevant to sport analysis.

2.3.2.1 Newton's laws of motion

Newton, who published his three laws of motion in his work *Philosophiae Naturalis Principia Mathematica in 1686* is often referred to as the father of modern mechanics. These three laws, which are originally designed for single particles are still the fundament of the contemporary biomechanics.

First law (*Law of Inertia*): An object "will remain in the state of rest or move in a straight line with constant velocity, if there are no forces acting upon" it (Nigg & Herzog, 1994, p. 37).

(1) If F = 0 then v = constant

Second law (*Law of Force and Acceleration; Law of Mechanics*): An object "acted upon by an external force moves such that the force is equal to the time rate of change of the linear momentum" (Nigg & Herzog, 1994, p. 37).

(2) $F = \frac{d(mv)}{dt}$ or F= ma

Third law (*Principle of Counteraction; Actio est Reactio*): When two objects "exert force upon another, the forces act along the line joining the" objects "and the two force vectors are equal in magnitude and opposite in direction" (Nigg & Herzog, 1994, p. 38).

(3) $F_{12} = -F_{21}$

2.3.2.2 Centre of mass

The Centre of mass (COM) "is a theoretical point at which the body's mass is considered to be concentrated" (Arus, 2012, p. 92). It is an essential concept in most inverse dynamic calculations as it defines the resistance arm of the lever system in a joint moment calculation.

2.3.2.3 Principle of the lever

The principle of the lever which was first explained by Archimedes (around 240 B.C.) states that a force system is balanced or is in equilibrium about a fulcrum/pivot, when "the total anticlockwise moment is equal to the total clockwise moment. Therefore, a lever will balance or turn uniformly about the point of support when the product of the force and force arm equals the product of the resistance and resistance arm" (Kent, 2006, p. 435)

This principle is the fundament of muscle force calculations as most joints can be defined as acting levers, with the joint centres' (as fulcrums) distance to the muscle insertion as the force arm and its' distance to the segmental COM as lever arm. Three types of levers can be differentiated (Figure 9), the first- (e.g. upper ankle joint/art. talocruralis for dorsal flexion), second- (e.g. lateral abdominal muscles/m. obliquus externus for thorax tilt) and third-class (e.g. knee joint/art. genus for leg flexion) levers, depending on joint, segment and muscle order.

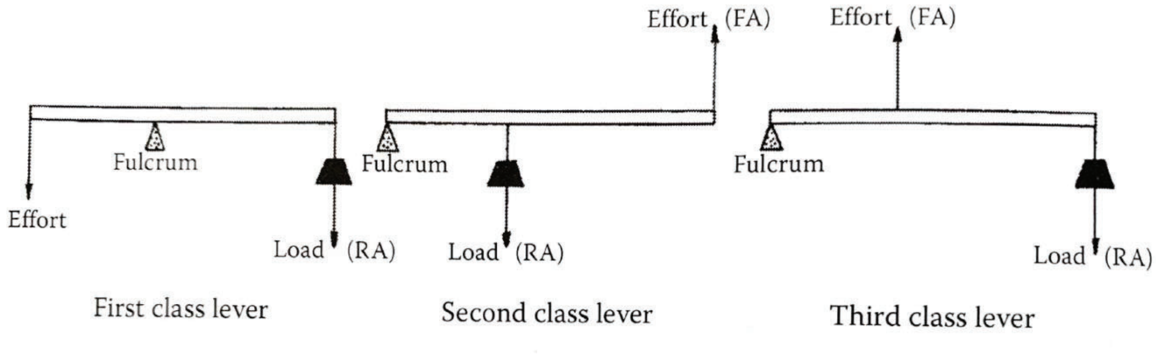

Figure 9: Different types of levers (Arus, 2012).

2.3.2.4 Law of Conservation of Momentum

The law of conservation of momentum states that in a closed system the total momentum is constant (Wagh & Deshpande, 2012, p. 164). This is particularly important when it comes to equations of motions, in example to calculate joint moments from a jump onto a force plate.

2.3.2.5 Law of Conservation of Angular Momentum

The law of conservation of angular momentum states that in a closed system the total torque about a given axis remains constant (Wagh & Deshpande, 2012, p. 212). This law is the fundament of the pulse transmission between segments in sports movements, e.g. proximal-to-distal movement sequences (PDMS; see 2.3.3.3).

2.3.2.6 Rigid body

Another simplification in most biomechanic studies is the assumption that the human body is a multi-segment system consisting of rigid segments. In particular, a rigid body is defined as “Matter that is assumed to occupy a finite volume in space and that does not deform if subjected to forces. A rigid body consists of a number of mass particles with the distance between any two particles being constant.”, however “the rigid body concept may“ only ”be valid where the deformations of the body are insignificant relative to the motion of the whole body” (Nigg & Herzog, 1994, p. 36). This assumption particularly leads to bias if the measuring method displays a strongly divergent reality. For example, motion capturing systems often record marker positions placed on soft tissue, which deform and change shape, whereas inverse dynamic calculations reference these markers and determine internal forces. As a result, biomechanic modelling is always a compromise between accuracy and complexity.

2.3.3 Selected sport biomechanic concepts

The mechanics’ fundamentals described in this research (see 2.3.2) lead to specific applications in biomechanics. An extract particularly necessary for the current study is described in this chapter.

2.3.3.1 Functional phases

A very common procedure to apply general mechanic laws to complex sport movements, is to divide them into consecutive sub-movements, which are comparable with simple mechanical operations. These sub-movements are called functional phases as part of the sequential action analysis. A practical example would be to define a functional phase for the lateral leg elevation to calculate pulse transmission of this pendulum-like leg elevation movement to the following leg extension movement of the kicking action.

2.3.3.2 Dynamic balance and stability in human motion

Dynamic balance and stability are basic requirements to perform sport techniques and particularly the foundation of effective power transmission. In example, if a fighter is not in a balanced position, during the impact of a kick on the target and does not react timely by changing the supporting conditions to provide stability, he/she will be forced to fall down with the kicking leg or body (see Figure 10). Therefore, the main difference between the explanation in physics and the practical implementation in sports biomechanics is that the athlete can internally react to the external impact and change his segmental position to adapt the supporting condition as needed to divert forces. In dynamic systems, such as sport movements, particularly with single foot support such as kicking motions, it can be derived that the higher the absolute distance between the centre of mass and the centre of pressure, the higher is the sensitivity of balance to external forces. On the other hand, stability as the ability to (mechanically) adapt to these balance changes, can be indicated by a low horizontal distance between the COM and the COP.

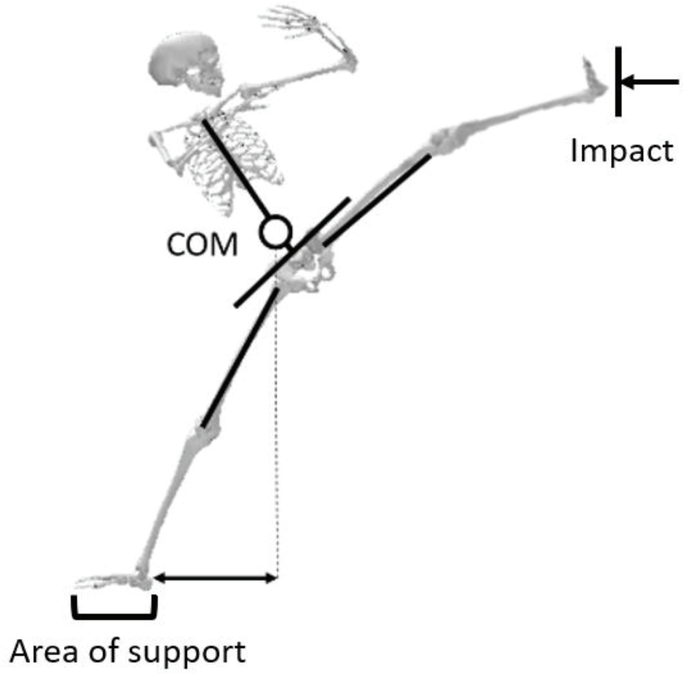

Figure 10: Unsupported section of a kick movement, illustrating necessity of dynamic balance during kick execution.

2.3.3.3 Proximal-to-distal movement sequences (PDMS)

Sport locomotion often aim to deliver maximum power outputs of single motion phases - sequences or full movements. These outputs are usually not achieved by independent motions resulting of single muscle contractions but rather by an interaction of pulse transmissions in multi segmental movements induced by several groups of muscles contracted in a specific sequence, called intermuscular coordination. These sequences often start with relatively small and slow movements of big and heavy segments, which transmits moments and (e.g. centrifugal) forces to the next body part and so on to ultimately increase the power output from the last segment of the kinematic chain. This concept is known as proximal-to-distal movement sequence (PDMS).

2.3.3.4 Muscle force-length relation

It is well known that a muscle can deliver different amounts of force in different joint angle positions. The "Force-length relations describe the relation between the maximal force a muscle (muscle fibre, or sarcomere) can exert and its length" (Nigg & Herzog, 1994, p. 168). In other words, a muscle can produces different amounts of force with different size. This knowledge helped to establish the *Cross-bridge Theory* which states that "cross-bridges extend from thick to thin filaments and cause sliding of the myofilament one after another. Each crossbridge is assumed to generate the same amount of force and work independently of the remaining cross-bridges. Since the cross-bridges are believed to be arranged at equal distances along the thick filament, overlap between thick and thin filaments determines the number of possible cross-bridge formations, and thus, the total force that may be exerted" (Nigg & Herzog, 1994, pp. 168-169). This Theory is illustrated in Figure 11 for the skeletal muscle of a frog. The force-length relation is of particular importance when it comes to full range of motion training exercises.

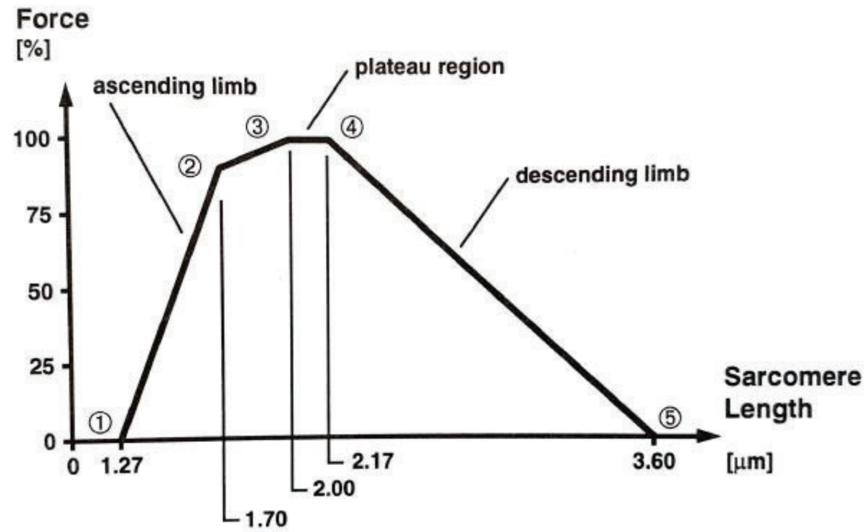

Figure 11: Theoretical force-length relation of isolated fibres of frog skeletal muscle (Nigg & Herzog, 1994, p. 169).

2.3.3.5 Muscle force-velocity relation

Another muscle characteristic describes the relation between the force and the movement velocity. Nigg and Herzog (1994, p. 173) define the force-velocity relation (Figure 12) as "the relation that exists between the maximal force of a muscle (or fibre) and its instantaneous rate of change in length. Force-velocity properties are determined for maximal activation conditions of the muscle and are typically obtained at optimal length of sarcomeres." The muscle force-velocity relation is of particular importance for maximum force estimation in sport device development.

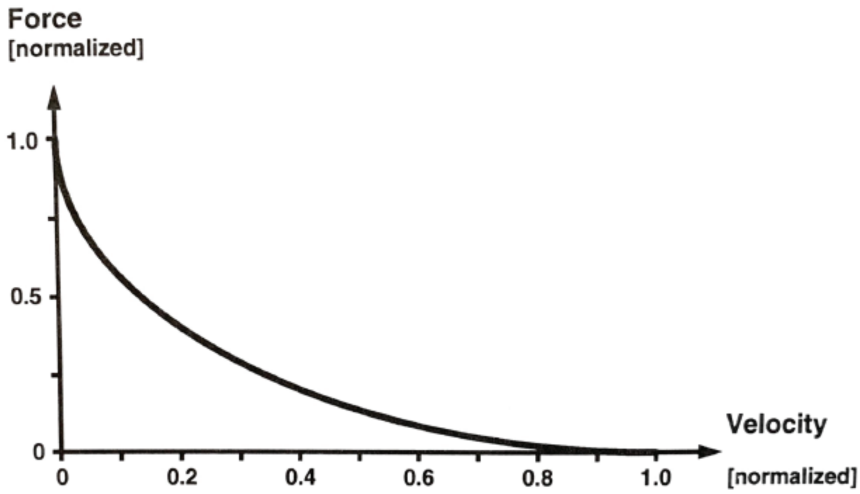

Figure 12: Normalized force-velocity relationship of concentrically contracting skeletal muscle (Nigg & Herzog, 1994, p. 174).

3. Biomechanical and physiological analysis in Martial Arts

Sports movement in general pose a considerable challenge to biomechanists as boundaries of human abilities are pushed beyond the currently known performance limits. Winning performance analysis requires deep understanding of body functions and actions including physical strain sequences. Biomechanics as the foundation of technique analysis and improvement as well as physiological and physical abilities as the basis for technique execution are believed to be the most important research areas to obtain the pre-requisites of every sport. Modern methodical approaches help us to “penetrate” into the body system actions.

3.1 Short excerpt of history in movement analysis and biomechanic

The roots of modern movement science reach very far back to ancient philosophers (e.g. Phytagoras, Hypocrates, Plato, Aristotle and Archimedes), mathematicians of the renaissance (e.g. Da Vinci) and the scientific revolution (e.g. Galilei, Kepler and Newton) (Nigg & Herzog, 1994, pp. 4-23). However, historically one of the first major breakthroughs of actual movement analysis were made by Etienne Jules Marey, who inter alia developed the “first serious force plate” between 1838-1902 (Nigg & Herzog, 1994, p. 27) and Stanford & Muybridge with their serial-photograph of a horse gallop to see the exact leg position in different movement sections in 1872. Finally, in the 20th century, biomechanics gained acceptance in science mainstream, as it became “a discipline at universities with graduate programs and faculty positions” (Nigg & Herzog, 1994, p. 33). The further technical development of high-speed cameras, motion capturing systems, EMGs, force plates, isokinetic analysis instruments and more led to the advanced and complex discipline, as which it is known today.

3.2 State of the art methodical approaches

3.2.1 Anthropometric, physical, and physiological abilities analysis

Studies on anthropometric, physical, and physiological abilities as the basis of performance and talent scouting, were performed on a large- scale compared to other fields in sport science. Moreover, it is believed that most results of striking Martial Arts, which include kicks (taekwondo, karate, or kickboxing) are transferable to each other. However, it is noted that particularly Pointfighting Martial Arts could deviate in specific performance characteristics, due to their very special set of rules even though the research methods might be similar.

Chaabene, Hachana, Franchini, Mkaouer, and Chamari (2012) provide a systematic review on *physical and physiological profile of elite karate athletes* including a wide spectrum of analysis systems, such as anthropometric measurements, somatotypes, bone mineral densities, aerobic and anaerobic profiles as well as jumping, strength exercise maximum performances and reaction times from 89 references in total. A similar approach was performed by Bridge, da Silva Santos, Chaabene, Pieter, and Franchini (2014) for taekwondo, including 131 references. Further analysis methods included skinfold measures, underwater weighing, Bio-impedance, x-rays, muscular endurance tests, speed and agility tests and flexibility tests.

A review of kickboxing studies in the fields of *anthropometric, psychophysiological and activity profiles and injury epidemiology* was performed by Slimani et al. (2017) with 69 references. Tabben, Chaouachi, et al. (2014) on the other hand compared jumping abilities, sprint abilities and strength exercises between Judo, Karate and Taekwondo athletes. Whereas Tabben, Coquart, et al. (2014) developed a *field aerobic karate specific test (KST) for karatekas.* Several other authors used the Wingate test to evaluate the anaerobic abilities of athletes (Slimani et al., 2017). It is noted that an interesting aspect for future studies would be to review and compare studies of Pointfighting and all other striking kick-involving Martial Arts with regards to the quoted methods.

3.2.2 Time motion analysis systems

Most common time-motion analysis in Martial Arts are based on images, including a classification of situations into high vs. low intensity and breaks. Ratios between these three characterisation are presented by Slimani et al. (2017). Figure 13 illustrates these results for kickboxing. Other approaches report percentages of the total match for specific actions. Clinching in Muay thai (Cappai et al., 2012) or grappling in MMA (Del Vecchio, Hirata, & Franchini, 2011).

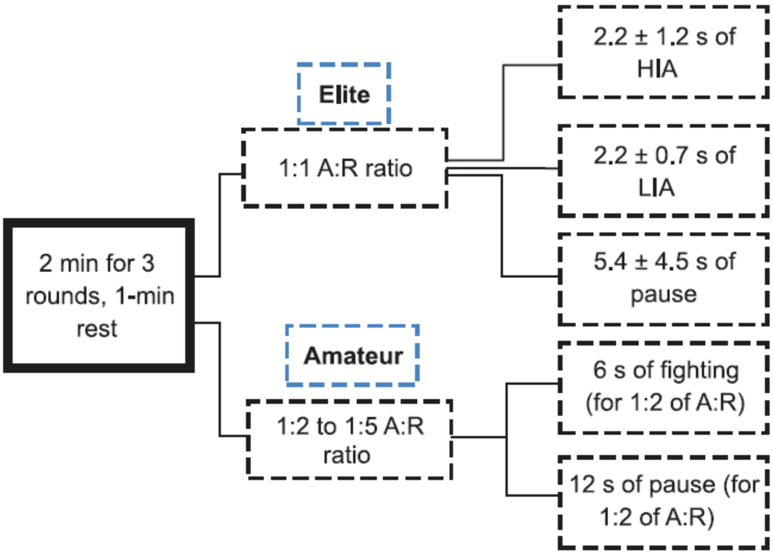

Figure 13: "The activity-to-rest ratio in elite and amateur level kickboxing matches. *Note:* HIA: high intensity activity; LIA: low intensity activity; A:R: activity-to-rest." (Slimani et al., 2017)

Besides image analysis there are investigations on physiological parameters, such as heart rate, lactate (Chaabène et al., 2014), VO_2 (Beneke, Beyer, Jachner, Erasmus, & Hütler, 2004) or other blood measurements (A. Moreira, Arsati, de Oliveira Lima-Arsati, Franchini, & De Araújo, 2010) but foremost during simulated fights and break time.

3.2.3 Sequential action analysis

Most sport techniques are *serial tasks*, which can be defined as "a task consisting of a series of several distinctive elements strung together to produce an integrated movement. The order in which the elements are performed is important" (Kent, 2006, p. 493). For comprehensive understanding of these complex interactions, biomechanists, as a first step tend to split the movement into functional phases based on the fundamental movement pattern[3] of each section. Combined, these sections are called sequential action. There are various methods for sequential action analysis. However, the first step is most likely a qualitative analysis based on images. Current standards reach from regular and high-speed videos to complex motion capturing systems like Vicon®.

[3] "A movement which forms part of a more complex skill" (Kent, 2006, p. 225)

In Martial Arts to date sequential actions have been analysed only for single leg techniques (Estevan, Falco, Silvernail, & Jandacka, 2015; Jemili, Mejri, Sioud, Bouhlel, & Amri, 2017; Zago et al., 2015), with the exception of Hoelbling, Preuschl, Hassmann, and Baca (2017) and a case study by Alsamad (2012) for multiple kicks. Functional phases are defined solely for the kicking leg's action (Quinzi, Camomilla, Di Mario, Felici, & Sbriccoli, 2016). However, knowledge about such movements is still rather insufficient, as no relative phase durations for multiple kicks were found. Furthermore, mainly kicking leg actions were analysed and other contributing motions were predominantly disregarded.

3.2.4 Balance and Stability analysis

Martial Arts and particularly kicking techniques constitute some of the most complex balance situations in sports, due to the single leg support, a jump/flight/slide phase, the highly dynamic execution, and the variety of influencing factors, such as acting external forces during the target contact. This might be the reason why balance studies in Martial Arts were solely for hand techniques (Cesari & Bertucco, 2008; Gulledge & Dapena, 2008) but not for kicks. It is stated that a first significant approach to cover this field would be to develop a model using indicators for balance and stability as a method to compare executions. Thereon based on and in combination with sequential analysis a complex calculation model should be proposed.

3.2.5 Flexibility analysis

Flexibility (as defined in section 4.2 Flexibility), testing can follow a variety of approaches, such as single and multi-joint, static, and dynamic, active, and passive ones. For Martial Arts kicking techniques, hip joint flexibility in all movement directions (flexion/extension adduction/abduction, internal/external rotation) is fundamental. As stated in section 2.2.1 Hip Joint (articulatio coxae) muscles, there are various single and multi-joint muscles involved, which merely cannot be tested under isolated circumstances (on living subjects). Therefore, authors propose different analysis or estimation methods. Tests for static hip flexibility like the toe-touch (Kippers & Parker, 1987) and side split tests (Amigó, Faciabén, Marginet, Ferrer, & Evrard, 2010) are simple to perform but only provide a crude estimate of maximum values for loosely defined inter-limb angles in static hold. Other authors propose peak values of the hip joint angles during technique execution (Preuschl, Hassmann,

& Baca, 2016). However, movement range for fast sport movements in Martial Arts techniques, is complex to analyse as synchronised multi-limb action is involved. The hip joint movement range during kick techniques involves a combination of all angles for both hip joints in addition to knee flexion. Therefore, a global measure cannot be extracted by summing up the joint angles for the individual legs', as those angles are inherent to the local coordinate system fixed at the joint centre of rotation and cannot be added directly in the 3D space. To solve this problem a simplified global measure that is less prone to bias and error based on kinematic data reduction (Miller, Chang, Baird, Van Emmerik, & Hamill, 2010; Witte, Ganter, Baumgart, & Peham, 2010) would be helpful. Such measure provides the means to assess and compare movement patterns across athletes.

3.2.6 Power generation analysis

Power generation in its' basic form is conducted by single muscle contraction as described in section 2.1.2 Muscular system. Most sport movements are based on simultaneous activation and co-activation of muscles in order to rotate the respective segment around a joint centre of rotation. However, in order to ultimately and efficiently increase the power output most techniques are using pulse transmission between segments. Therefore, they can also be described as serial tasks, which are defined in section 3.2.3 Sequential action analysis. This leads to force summation, "the combination of forces produced by different parts of the human body (…). In theory the strongest and lowest body parts around the *centre of gravity (e.g. trunk and thighs), followed by the weaker, lighter, and faster extremities. This is known as sequential acceleration and results in successive force summation" (Kent, 2006, p. 219). In biomechanics this is also known as PDMS (see, section 2.3.3.3 Proximal-to-distal movement sequences (PDMS)).

PDMS have been successfully applied to Martial Arts punches (Fuchs, Lindinger, & Schwameder, 2017) and rear-leg kicks (Kim, Kim, & Im, 2011; Sorensen, Zacho, Simonsen, Dyhre-Poulsen, & Klausen, 1996) but surprisingly front leg actions were never considered.

3.2.7 Calculation of hip joint moments

The calculation of the hip joint moment is highly dependent on the exact position of the joint centre. This is calculated using the marker positions, manually entered anthropometric data and the Newington-Gage model (Vicon®, 2016). To calculate the joint moments, chord functions including segmental masses and mass centres (based on distribution models) are used. External forces (e.g. Flexibility Trainer) can additionally be manually calculated, using the raw data of the Vicon® outcomes and add additional forces (measured at the device) in the respective distance to the joint centre.

4. Physiological and biomechanical pre-requisites for Martial Arts kicks

Martial Arts kicking techniques depend on a variety of physiological and biomechanical factors, as not only actively participating segments (e.g. legs) contribute to the movement goal but insufficiently stabilized or sub-optimally positioned, passive segments significantly counteract it. For example, when the leg is elevated, a reclined thorax can shift the COM (centre of mass) behind the supporting leg and inhibit the forward movement or destabilize the fighter during target contact (see Figure 14).

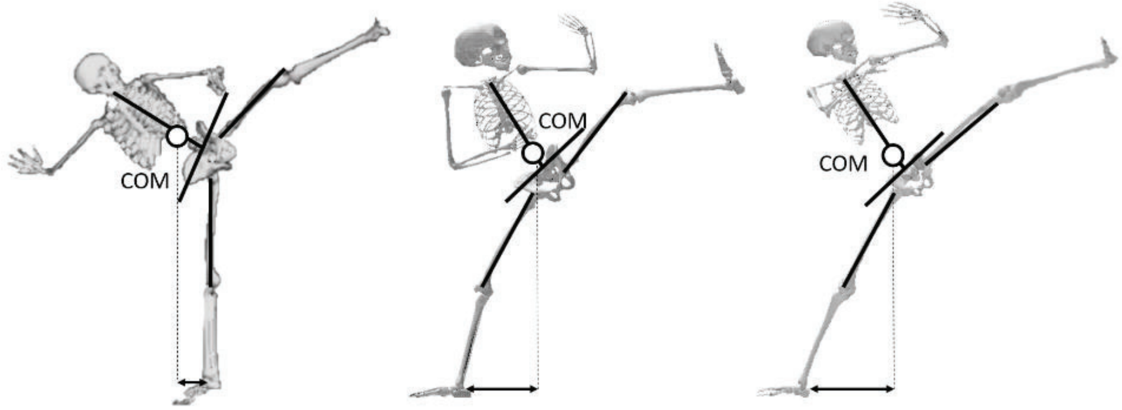

Figure 14: Different kick executions, contributing to COM positioning.

Generally, four physical or conditional abilities, namely strength, endurance, speed, and flexibility are identified. However, there are also a number of mixing forms and combinations with cognitive abilities, illustrated in Figure 15.

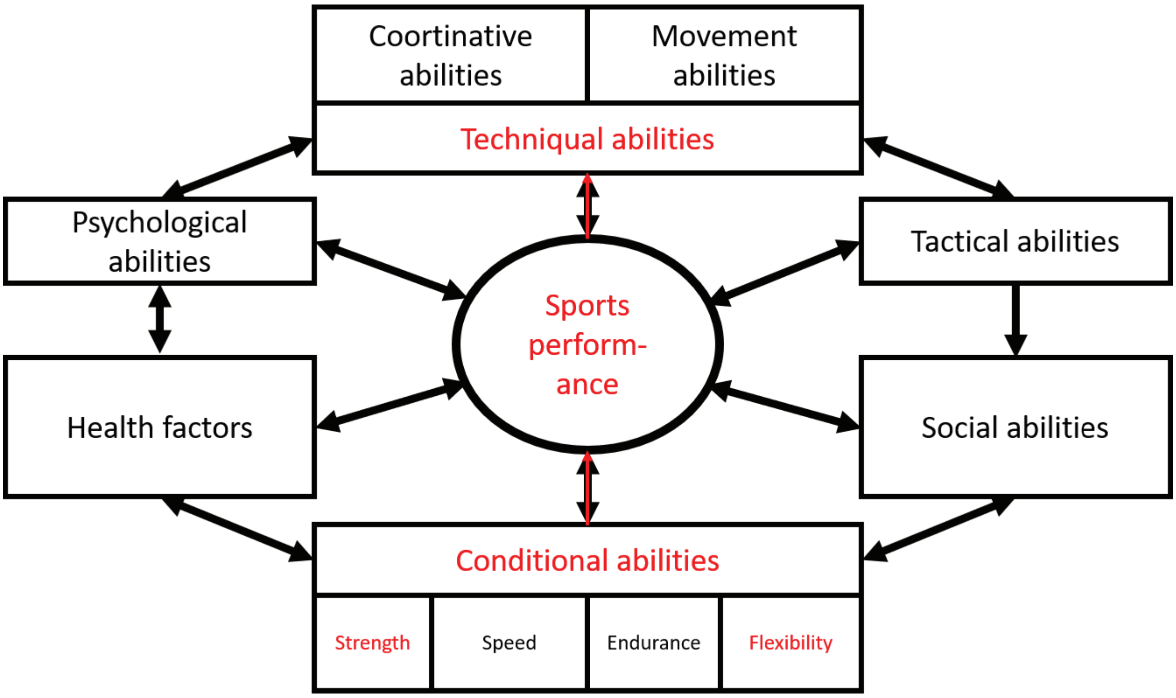

Figure 15: Simplified model of sports performance components adapted from Weineck (2007, p. 25). Selected key abilities for the current sport device development and their contribution are marked in red.

However, in order to analyse complex sport movements and thereon develop a sport specific device, it is necessary to firstly select critical abilities to improve and then further reduce the volume of analysed data into understandable quantities. Therefore, models must be developed to simplify the relevant physiological and biomechanical functions as well as to decrease the observed number of interactions or counteractions, by only focusing on specific pre-requisites. The COM for example, is one of the fundamental simplifications in physics and biomechanics.

Basic qualitative analysis of Martial Arts kicking techniques identified the fundamental requirements for a successful execution. Strength and flexibility in both hip joints in combination with several coordinative abilities (e.g. balance) summarized as technique skills are needed to initiate a pelvis tilt from the supporting leg and elevate the kicking leg far enough to reach the target.

4.1Strength

Muscular strength in general can be defined as “force or tension that a muscle or (…) a muscle group can exert against a resistance in one maximum effort” (Kent, 2006, p. 366). In biomechanics, temporary muscular strength is described by the contraction force a muscle applies between its’ origin and insertion. However, “there are a number of different types of strength”, such as “absolute strength, dynamic strength, elastic strength, explosive strength, one repetition maximum; relative strengths, specific strength, starting strength, strength deficit, strength endurance, static strength” (Kent, 2006, p. 531). Definitions of these types of strength, which maybe of high importance for the context of the current research can be found in Table 3.

Table 3: Definitions for different types of strength form (Kent, 2006, p. 5; 172; 197; 464; 513; 526)

Absolute strength	The maximum force an athlete can exert with his or her whole body, or parts of the body, irrespective of body size or muscle size.
Dynamic strength	The ability to exert muscular force repeatedly or over a period of time. It is especially concerned with forces which produce or change the motion of a mechanical system.
Explosive strength	The ability to expend energy in one explosive act or in a series of strong sudden movements as in jumping or projecting some object (e.g. javelin) as far as possible.
Relative strength	The maximum force exerted in relation to body weight or muscle size.
Specific strength	The strength of a particular type of muscle action. A person who has a high level of strength for one type of muscle action does not necessarily have a high level of strength for other types.
Starting strength	The strength recorded 30ms after the start of a muscle action.

4.2 Flexibility

Flexibility is defined very differently in the literature. The Oxford dictionary of sport science and medicine defines it as "the ability to move a joint smoothly through its complete range of motion" (Kent, 2006, p. 214), whereas other authors define it more specifically as the capacity of the structures that make up the tissues such as muscles, tendons and connective tissues, lengthen through the available range of motion (ROM; defined below) minimizing the joint passive torque, the muscle tendon-stiffness (passive) and the opposite force generated by the antagonist muscle contraction (active) (Alter, 2004; P. V. S. Moreira & Gonzaga, 2012). Another description of its limiting factors is "flexibility is determined by the nature of the joint structure, the condition of the ligaments and fascia that surround the joint, and muscle extensibility. Flexibility may also be limited by the skin, connective tissue and bones around the joint" (Kent, 2006, p. 214).

Flexibility is an important pre-requisite for successful and injury-free kicking execution in Martial Arts (Probst, Fletcher, & Seelig, 2007) and is "one of the main components of physical fitness and is believed to be important for optimum health" (Kent, 2006, p. 214).

The ability is naturally limited in relation to daily movement range demands to provide joint stability. Thus, ROM declines considerably with age and periods of immobility (Roaas & Andersson, 1982). Joint stability is normally achieved by antagonistic muscle co-contraction (simultaneous contraction of agonist and antagonist) (P. V. S. Moreira, Goethel, & Gonçalves, 2016; Thibordee, 2014), thus impairing the optimal manifestation of flexibility or ROM during Martial Arts kicking (P. V. S. Moreira, Jaimes, & Menegaldo, 2019).

Generally, there are 2 types of flexibility, static and dynamic flexibility.

4.2.1 Static flexibility

Static flexibility describes "the range of motion of a joint, when the body segment is passively moved (e.g. by an exercise partner) and held in position." (Kent, 2006, p. 527)

4.2.2 Dynamic Flexibility

Dynamic flexibility is "the range of motion that can be achieved by actively moving a body segment using muscle actions. Dynamic Flexibility also refers to the relative ease of making rapid and repeated movements over a range, rather than the range itself" (Kent, 2006, p. 172).

4.2.3 ROM

As stated above, the term *range of motion (ROM)* is clearly associated with *flexibility*. Unfortunately, the exact definition of ROM differs widely between research manuscripts. ROM describes "the angle through which a joint moves from the anatomical position to the extreme limit of its motion in particular direction" (Kent, 2006, p. 455) or simply as the static flexibility (Alter, 2004, p. 3). However, there are other usage cases for this term, which are particularly based on limiting factors as their logical result. Sometimes it is defined as the full movement potential of a joint (Faisal et al., 2019), which theoretically renders the skeletal system as limitation of ROM. Other authors describe it as maximum voluntary movement potential of a joint, which additionally involves muscles, ligaments and tendons as limitations (Eston & Reilly, 2013, p. 129). Furthermore, it is associated with the maximum range within a specific exercise. Others argue that it is the current movement range in a specific sport technique. Therefore, this research proposes a nomenclature for all above in Table 4.

Table 4: Range of motion and movement range definitions for the current research.

Abbreviation	Term description	Specification
ROM_{Max}	Maximum range of motion	Maximum movement potential of a joint, limited by the skeletal system.
ROM	Full range of motion	Full voluntary movement range during passive stretch exercises.
$MoRa_{Max}$	Maximum movement range	Maximum range during a technique execution.
MoRa	Current movement range	Sub-maximum range during a technique execution.

4.2.4 Research on flexibility in Martial Arts

As static flexibility test in Martial Arts, the Sit and Reach (S&R) test is very common (Bridge et al., 2014). The test in international senior male taekwondo athletes scored 36-36.9 cm and in female 35.2-56.6 cm, which lies between the 70-100th percentile for males and females between 20-29 years (Bridge et al., 2014; Hoffman, 2006). However, it is noted that the S&R test is dependent on anatomical data, such as leg and arm length and therefore, does not present an exact measure for hip joint flexibility. Other but far less authors present data for combined (leg side split) or single leg abduction. Fong, Ng, and Chung (2013) declare a leg side split angle of 107.90° ± 24.80 (9 male; 1 female), while Toskovic, Blessing, and Williford (2004) states 152.3° ± 8.3 (experienced) and 115.3° ± 8.3 (novice) for their male and 130.6° ± 14.4 (experienced) and 134.6° ± 12.6 for their female groups. Podrigalo, Volodchenko, Rovnaya, and Stankiewicz (2017) however, report in-balanced hip abductions of 86.50° ± 10.30 for the left and 97.69° ± 7.16 for the right leg within their advanced group and of 80.48° ± 4.98 for the left and 86.50° ± 6.25 for the right leg within their beginner group of kickboxers, using goniometer testing.

4.3 Technique skills

Movement skills can be divided into 2 different classes, namely general and specific technique skills. Sport techniques count as specific skills and are based on a variety of abilities and result in different manifestations (see, Figure 16).

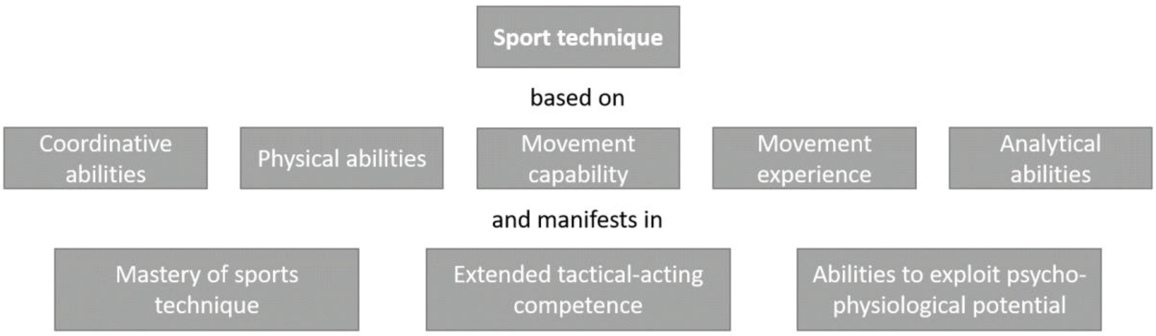

Figure 16: Schematic overview of fundamentals and manifestations of sport technique, translated and adapted from Weineck (2007, p. 835)

However, as specific technique training in Martial Arts is primarily coordinative and just little physical, therefore it is necessary to particularly discuss the different coordinative abilities needed to store and optimize new motor engrams[4], such as reaction, rhythm, balance, kinaesthetic differentiation and space – time orientation (Hirtz, 1985, 1997). Definitions of these skills are illustrated in Table 5.

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[4] Motor engrams are „memorized motor patterns used to perform a movement or skill, that are stored in the motor area of the brain" (Kent, 2006, p. 355)

Table 5: Definitions of coordinative abilities. Retrieved from Kent (2006, p. 66; 139; 303) and Schnabel and Meinel (1976, pp. 251-255)

coordination	The ability to integrate the action of different parts of the body to produce smooth, successful movements.
reaction	The ability for fast initiation and execution of adequate, short-time motoric actions on a signal.
rhythm	The ability to identify and motorically reproduce an external rhythm as well as to implement an internalized rhythm in an own movement.
balance	The ability to maintain a stable and specific orientation in relation to the immediate environment.
kinaesthetic differentiation	Awareness of body and limb position and movements
space – time orientation	The ability to determine and change the position and movements of the body in space and time.

All afore listed abilities are of importance for Martial Arts kick executions. Fast measured reaction to the opponent actions, dynamically fluctuating external forces (target contact) and other external factors is needed to adapt to all circumstances. Rhythm is needed to time all single actions in order to achieve the best overall outcome. Dynamic balance is particularly important as the basis of a kick execution as insufficient support during specific movement sequences would lead to a fall of the executor. Furthermore, the is also a precursor for successful power generation and force transmission to the target. Kinaesthetic differentiation serves as the underlying ability to perform the right segmental position changes. Space- time orientation enables the athlete to e.g. estimate distances and progress with each movement part at the right moment.

5. Current training methods

As stated in section 4 Physiological and biomechanical pre-requisites for Martial Arts kicks, strength and flexibility are selected as training abilities limited by the framework conditions of the current sport device development. Both abilities can be trained in different ways using a variety of classical or rather modern methods.

5.1 Classical Strength Training Methods

Classical strength training methods can be generally differentiated by their purpose of development or their characteristic physiological or neuronal response (Figure 17).

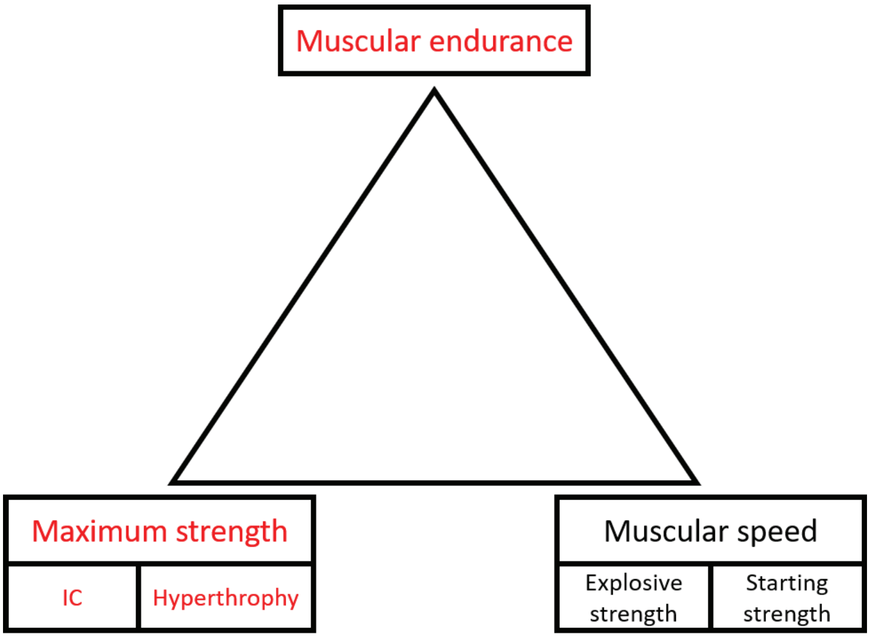

Figure 17: Three main types and sub-types of strength training, adapted from Weineck (2007, p. 372). Key training methods for the sport device development are marked in red.

These strength training methods can be differentiated by the number of repetitions and the percentage of maximum resistance, an athlete can perform in one set. A schematic illustration of different strength training methods and their relation to the maximum number of set repetitions is shown in Figure 18.

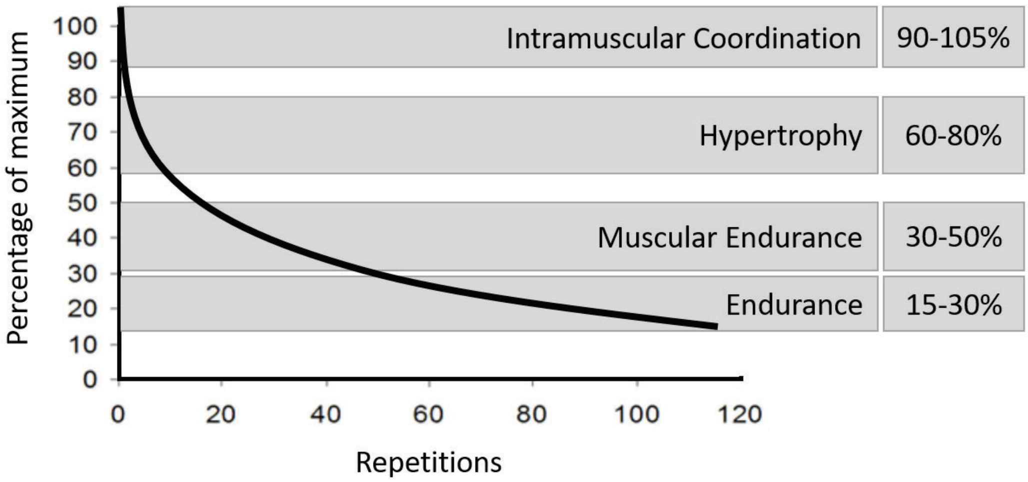

Figure 18: Schematic illustration of different strength training methods.

5.1.1 Maximum strength

Maximum muscle strength is dependent on two main factors, the cross-sectional area of the individual muscles, and the intramuscular coordination. Maximum exercise strength further depends on intermuscular coordination and is often described as one repetition maximum (1RM)

5.1.1.1 Intramuscular Coordination Training (ICT)

Intramuscular strength is determined by the number of muscle fibres a person can voluntary, simultaneously activate. ICT is conducted using near maximum (90-100% of 1 RM) or even supra-maximum (-105% in eccentric motion) resistances, which can only be lifted (or resisted against) 1-3 times (Figure 18). Adaptions are mostly neuronal, particularly ICT leads to a higher rate of muscle fibre activation within a muscle.

5.1.1.2 Hypertrophy Training (HT)

Hypertrophy in this context describes the production of new muscle structures. Classic hypertrophy training is used to extend the cross-sectional area of a muscle (most notably for Bodybuilders but applicable to majority of sports). Physiologically, HT aims to damage the muscles' protein structure, and this way invoking a healing process in which more structures are produced. It is claimed that the HT area is around 12 (exhausting) repetitions with 60-80% of the 1RM per set, even though training recommendations vary. Both, ICT and HT lead to an increase of maximum strength.

5.1.2 Muscular endurance

Muscular endurance is foremost based on the nutritional behaviour of the muscle cells mainly on the oxygen delivery into the citrate cycle within the cell. Classical training is performed between 20 and 40 (exhausting) repetitions with 30-50% of the 1RM.

5.1.3 Muscular speed

Muscles speed training is discussed controversially as the ability is particularly based on intramuscular coordination. Therefore, the main training method for muscular speed should be ICT. However, particularly if high resistance training is counterproductive for the sport or the training period, a large variety of other approaches are used ranging from 1-10 repetitions, using near 0 -50% of the 1RM, combined with maximum movement speed. One key idea of these methods is to perform movement techniques within about 10 seconds, where the energy supply is mostly based on adenosine-triphosphate (ATP) and creatine phosphate (CP). This phase is called anaerobic-alactacid phase as the energy supply works without external oxygen but does not produce lactate.
Pure speed can be tested with *reaction speed*, *action speed* and *frequency speed* assessments (Weineck, 2007, p. 610).

5.1.3.1 Explosive strength

Explosive strength is “the ability to expend energy in one explosive act or in a series of strong sudden movement as in jumping, or projecting some object (e.g. a javelin) as far as possible” (Kent, 2006, p. 197). A typical training method is plyometric training, which commonly consists of a series of jumping and stepping movements.

5.1.3.2 Starting strength

Starting strength is “the strength, recorded 30ms after the start of a muscle action” (Kent, 2006, p. 526). Compared to explosive strength it is rather trained without counter-movements. In essence the athlete tries to generate maximum power from a “resting” state of the muscle.

5.1.3.3 Complex speed

Complex speed is not solely dependent on the shortening speed of a single muscle but rather on the speed and interaction of several muscles in relation to a task (Weineck, 2007, pp. 610-613). Therefore, complex technique speed includes anticipation, technique ability, as well as inter- and intramuscular strength as important components.

5.2 Modern Strength Training Methods

Besides traditional strength training, there are several modern methods, such as EMS (electrical muscle stimulation), vibration training, proprioceptive (or functional) strength training and more. However, in this study the focus relies on two methodical approaches, namely isokinetic and full range of motion strength training.

5.2.1 Isokinetic strength training

Isokinetics in general describes “exercise with an accommodating resistance and a fixed speed” (Brown, 2000, p. 6). Therefore, isokinetic training can be defined very differently, depending on how narrow the approach is attended. An isokinetic contraction would mean that the rate of length reduction in a muscle would be constant. Another definition, which is the fundament of isokinetic analysis devices but not necessarily involves isokinetic contraction, focuses on a constant angular rate of change for the respective joint. The most global approach, which is used for the current sports device development, relates to the constant translation velocity of the most distal segment (foot). Isokinetic strength training is usually performed at angular velocities below 90°/s (Brown, 2000, p. 173).

5.2.2 Full range of motion strength training (serial hypertrophy)

Full range of motion strength training might not be a fully separated methodical approach as most exercises can be performed in this manner. However, recent studies show that this type of practice result in physiological adaptions related to flexibility training (Csapo, Alegre, & Baron, 2011; Franchi et al., 2014; Rowlands, Marginson, & Lee, 2003; Sharman et al., 2006). This physiological adaption is called serial hypertrophy, where additional muscle fibre sarcomeres are produced to ultimately increasing the muscle length. Thereby eccentric training leads to significantly higher adaptions in muscle length than concentric training (Csapo et al., 2011; Franchi et al., 2014).

5.3 Classical Flexibility Training Methods

Flexibility training or stretching is defined as "a linear deformation of tissue that increases its muscle length. Exercises involving muscle stretching are performed to maintain or improve flexibility" (Kent, 2006, p. 534). Stretching can be performed in a number of varieties and forms (see, Figure 19). However, the most common distinctions can be found at the upper two levels of Figure 19. Namely, static & dynamic and active & passive stretching. Weineck (2007, pp. 735-790) recommends a maximum of 1-2 trainings a day with 15 repetitions and 3-5 rounds, depending on intensity for these classical methods.

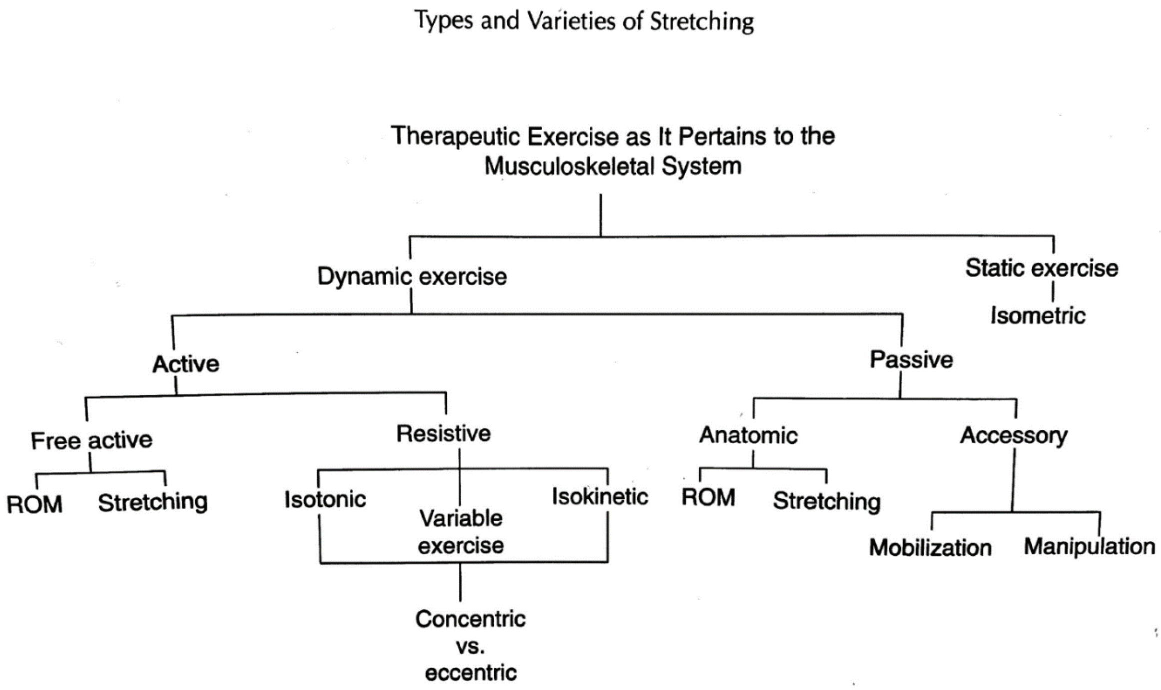

Figure 19: The categorization of therapeutic exercise in the treatment of the musculoskeletal system (Irrgang, 1993).

5.3.1 Static stretching

Static stretching is "a form of stretching in which a stretched position is held for a given duration (6-60s). Static stretching avoids forced movements that can provoke a stretch reflex" (Kent, 2006, p. 527). Recommendations are that stretches should take from 10-60s for each muscle (Weineck, 2007, p. 751).

5.3.2 Dynamic (or ballistic) stretching

Dynamic or ballistic stretching describes a "type of stretching in which an individual performs quick bouncing actions, which force the muscle to lengthen. The lengthened muscle reflexively contracts" (Kent, 2006, p. 67), due to muscle spindle reflex. Recommendations are that stretches should take from 10-30s of each muscle (Weineck, 2007, p. 752).

5.3.3 Active stretching

Active stretching is defined as "a stretch performed by assuming a position and then holding that position, using only the action of the agonist muscles. In the process the antagonistic muscles are stretched and relaxed by reciprocal inhibition. Typically stretches are held for 10s" (Kent, 2006, p. 13). For training recommendations, see 5.3.2 Dynamic (or ballistic) stretching.

5.3.4 Passive stretching

Passive stretching is characterized by "a stretching force other than that of the subject's own muscle actions (e.g. gravity or a force applied by a partner). Passive stretching can carry a movement beyond the normal active range" (Kent, 2006, p. 406). For training recommendations, see 5.3.2 Dynamic (or ballistic) stretching.

5.4 Modern and Unconventional Flexibility Training Methods

Current research focuses on mechanisms and methodical approaches, which can lead to larger training adaptions, than conventional methods. Particularly PNF methods (described below) seem to be superior.

5.4.1 Proprioceptive neuromuscular facilitation (PNF)

PNF flexibility training describes "an effective stretching technique for increasing the range of motion of joints. All PNF procedures require a partner and involve some pattern of alternating contraction and relaxation of the muscles being stretched, so that Golgi tendon organs are stimulated" (Kent, 2006, p. 441). It is noted that contrary to the cited definition, some studies already performed their training intervention without a partner, using different tools (e.g. towel) for stretching the joint muscles (Gärtner, 2013).

The advantage of the PNF method is situated on the central nervous level. Autogenic (see, section 2.1.3.1 Autogenic inhibition) and reciprocal inhibition (see, section 2.1.3.2 Reciprocal inhibition) are used to stimulate Golgi tendon organs and consequently inhibit the respective motor neurons, as described in section 2.1.3 Nervous system. Based on the sequence of contraction and relaxation of the muscles, two types of PNF training versions can be distinguished.

5.4.1.1 CRHR

CRHR means 'contract> relax> hold> relax' and contains a passive placement of the target muscle (TM) into a stretching position following an isometric contraction. After that the respective segment is passively moved to a greater stretch position (Sharman et al., 2006). Typical training sequences are illustrated in Table 6.

5.4.1.2 CRAC

CRAC means 'contract> relax> agonist contract' and combines a contraction of the TM, followed by a relaxation and a contraction of the opposing muscle (OM) to reach a wider position and culminates in additional passive stretch (Sharman et al., 2006). "Several studies have demonstrated that PNF stretches that incorporate a shortening contraction of the OM to lengthen the TM achieve greater gains in ROM and this effect is often attributed to reciprocal inhibition" (Sharman et al., 2006). Typical training sequences differ but a combination of three author statements is illustrated in Table 6.

Table 6: Training sequence of different PNF methods, based on Gärtner (2013, p. 94), Rowlands et al. (2003) and Sharman et al. (2006)

CRHR	**CRAC**
1) Adopt maximum position	1) Adopt maximum position
2) Contract TM 2-10s	2) Contract TM 2-10s
3) Relax TM 2-3s	3) Relax TM 2-3s
4) Passive stretch of TM 20s	4) Contract OM 5-10s
1-3 repetitions	1-3 repetitions

5.4.2 Other methods

Other, rather unconventional training methods are described in Table 7.

Table 7: Unconventional stretching methods, based on Alter (2004, pp. 190-194)

Method	Short description
Muscle energy techniques	A form of PNF stretching but with specific force and counterforce definitions.
Strain- Counterstrain	Describes a form of stretching after injury, where position changes during stretching lead to reduced pain and spams.
Functional technique	Like the functional technique, but the end position is “one in which the tension of tissues around the joint are equal” (Alter, 2004, p. 191).
Traction techniques	A form of therapy and mobilization, where “longitudinal tensile force is applied to a part of the body to stretch soft tissues or separate articular surfaces” (Alter, 2004, p. 192)

6. Current training devices

6.1 Relevant market products

An online search for flexibility training devices resulted in a large variety of sport gadgets for mainly passive ROM extension, categorised in Table 8.

Table 8: Results of market search on flexibility training devices. Exemplary pictures are illustrated in Appendix B.

Device category	Description	Source
Rigid straps	Rigid straps, most likely with flaps and often with different types of pulley blocks to take a position for static, passive stretches.	Stand (2020)
Flexible straps	Rubber-like straps or loops, often with flaps, to support a position for nearly static, passive stretches	Stretch (2020)
Foam Rollers	Most likely cylindrical of spherical foam rolls for fascia massages	ProsourceFit (2020)
Passive positioning devices	Devices, which are designed to help getting in stretching positions, without regulatory options to increase or decrease the stretch	Machine (2020); ProStretch (2020)
Active positioning devices	Devices, which are designed to help getting in stretching positions, with regulatory options to increase or decrease the stretch	Fitness (2020)

6.2 Relevant patented devices

The current devices on the market differ widely from the patent situation. It has been found that most products on the market cannot be associated with patents and most patents were not located at the market research. Table 9 shows patents of products associated with flexibility training.

Table 9: Patented devices for flexibility training.

Device category	Description	Source
Strength training device	A device for strength training of hip joint adductors and abductors, with constant resistance. ➢ Limited ROM ➢ Constant resistance (liquid based) ➢ Sitting position	Brentham (1978)
Passive flexibility training device	Devices for supra-maximum ROM strength training (< 200°) ➢ Passive stretching devices ➢ Adjustable (crank arm; rolls)	Ballet and Norwalk (1988); Chenera (1983); Oexle (2011); Ruff (1984); Winiels, Rave, and Vellinge (1994)
The Flexibility Trainer	Preliminary patent of the "Flexibility Trainer", which is analysed in the current study.	Hoelbling (2016b)

7. Technique selection (double side kick)

The main criteria for analysing-technique selection are based on a compromise between simplicity and complexity. The chosen technique needs to be complex enough to comprise a high enough level of difficulty to allow for clear differentiation between skill levels but simple enough that all participants can perform it. It is further noted that particularly a preferably big number of high-level athletes should participate at the study, which consequently involves international participation and additionally adds the limitation of language barriers for movement explanation. Therefore, the technique must be easy enough that its description is understandable, accordingly.

Following these criteria, the double side kick (see, Figure 20) was chosen for analysis. Particularly, in modern Martial Arts it is a frequently used competition technique (Ouergui, Hssin, Franchini, Gmada, & Bouhlel, 2013; Siska & Brodani, 2017). The double side kick is normally started from a double foot support/jumping movement, called ‘bouncing’ (Yuncza, 2011) or ‘hopping’ (Young-Kwan & Yoon Hyuk, 2011), leading to a combination of two lateral front-leg kicks, without dropping down the kicking leg in between. The second kick aims to reach the target, using a thrust movement with a 90° dorsal flexed ankle. The chambering position of this technique normally occurs between the two other lateral kicks, namely roundhouse and hook kick. Lateral kicks are notionally characterized by a main leg elevation movement projected on the coronal plane and a kicking movement projected on the transversal plane. The technique provides a high level of distinctiveness and freedom, particularly for the first kicking movement as the execution style is not limited by framework conditions, such as defined kick height or exact thrust direction.

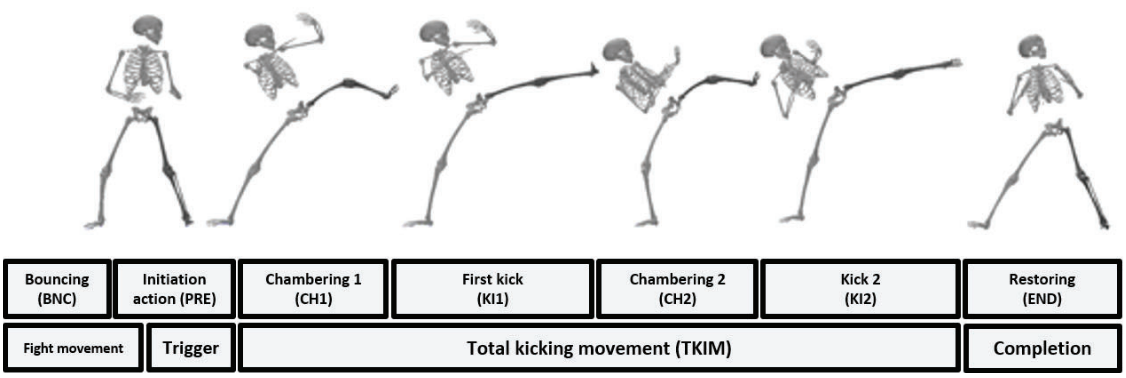

Figure 20: Double side kick illustration.

8. Aims

8.1 General aim

The general aims of this research are to (a) achieve comprehensive understanding of complex Martial Arts kicking motion by identifying performance contributing factors in order to (b) develop a training device for the enhancement of respective techniques based on state-of-the-art training methods as well as to (c) test the equipment for short-term general and sport-specific adaptions.

Therefore, the research is organized in two sections, technique performance factors exploration and equipment test.

8.2 Technique analysis

Based on section 4, Physiological and biomechanical pre-requisites for Martial Arts kicks, the author has extracted the analysis fields sequential action, balance and stability, power generation, initiation action and flexibility, to identify significant patterns for kicking success.

8.2.1 Sequential action

In order to extend existing functional phase definitions, it is aimed to identify appropriate kinematic characteristics for the supporting leg (SL), kicking leg (KL), pelvis and thorax actions and contribute to superior kicking performance.

8.2.2 Balance and Stability

To compare balance and stability conditions between athletes, based solely on kinematic data, it is aimed to develop models, which can be used to differentiate between skill levels.

8.2.3 Power Generation and Transfer

To analyse the power transfer between the segments of the main movement elements (leg elevation and kick movement) consequently contributing to the power generation for the kicks, it is aimed to identify and compare proximal-to-distal movement sequences.

8.2.4 Initiation action

As the literal foundation for power generation, initiation actions are performed by the athlete in order to execute the transition from double, to single leg support, while maintaining suitable supporting conditions and to simultaneously generate muscular tension for follow-up movement sequences. However, these actions can lead to a disadvantage as opponents might be able to detect them and thereby increase their time to react. Therefore, to comprehensively understand these movements, it is aimed to identify different patterns, motion amplitudes and starting times, based on the supporting leg (SL), the kicking leg (KL), the thorax and arm movements and relate them to biomechanical functions.

8.2.5 Flexibility

To understand the flexibility requirements, it is imperative to (a) define a global measure that provides simple means for differentiation between skill levels in hip joint ROM during fast sports actions and thereon based to (b) establish the necessary levels of static flexibility and submaximal dynamic range of motion during Martial Arts kick technique execution for different performance levels.

8.3 Equipment test

The prototype test will be performed in different levels. Firstly, the general functionality must be analysed. Secondly, general (unspecific) adaptions during one training session will be assessed. Lastly sport specific adaption during one training session will be analysed.

8.3.1 General functionality

The aim of the general functionality assessment is to evaluate training device specific data, such as movement speed, movement ranges and ankle tilt angles.

8.3.2 General adaption analysis

The aim of this section is to analyse general (unspecific) adaptions during a training session by comparing pre- and post-training flexibility tests.

8.3.3 Sport specific adaption analysis

The final analysis aims to compare kick specific, pre-, and post-training variables, determined by the previous technique analysis studies.

9. Hypotheses

The following section contains the general hypotheses of this research, while specific hypotheses are given in the respective research paper.

9.1 General functionality

H1: The device works force independently, with nearly constant movement velocity, defined by less than 30% standard deviation from the average.

9.2 General adaption analysis

H2: There is a significant difference in static (flexion and abduction) flexibility test outcomes between pre- and post-training assessment.

9.3 Sport specific adaption analysis

H3: There are significant differences in selected sport performance related metrics between pre- and post-training assessment of double side kick executions.

II. Practical implementation of the research project

The empirical section of the dissertation (III Publications) is performed in 3 steps (A-C), consisting of 5 publications, with the ultimate aim to develop a sports device for significant improvement of physical pre-requisites as well as sport specific performance of Martial Arts kicks.

A) The first step is to identify performance indicators of the execution of a complex Martial Arts kick (double side kick), by applying state-of-the-art kinematic models to different aspects of the motion:

   Publication 1: Sequential action, power generation and balance characteristics of a Martial Arts kick combination.

   Publication 2: Kinematic study of initiation actions and their biomechanical functions of a front leg kicking combination in Martial Arts.

B) Based on the established knowledge on biomechanical functions of the technique, a model is developed to cumulate performance indication into a simple measure describing sport specific ROM and comparing it with static flexibility:

   Publication 3: A kinematic model for assessment of hip joint range-of-motion in fast sport movements using spreading angles.

C) Combining previously mentioned papers, with state-of-the-art training methods a sports device is designed and tested:

   Publication 4: The Flexibility Trainer: Feasibility Analysis, Prototype- and Test Station development for a Sports Device for Hip-Joint Flexibility and Strength Enhancement.

   Publication 5: Acute Response on general and sport specific Hip Joint Flexibility to Training with Novel Sport Device.

III. Publications

10. Publication 1: Sequential action, power generation and balance characteristics of a Martial Arts kick combination

Publication status: The following manuscript was accepted by the International Journal of Performance Analysis in Sports on 23/05/2020 (Hoelbling, Baca, & Dabnichki, 2020b). Prof. Baca and Prof. Dabnichki contributed planning, proof-reading, and continuous assistance at the writing process to this paper. Literature search, test implementation and manuscript writing, was performed by Dominik Hoelbling.

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Sequential action, power generation and balance characteristics of a martial arts kick combination

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ABSTRACT

This paper presents a kinematic analysis of a kick combination action: Commonly performed, functional motion sequences are identified and, focusing on balance and sequential action characteristics, a classification of different kicking patterns of Pointfighting Martial Arts athletes is suggested. Vicon® motion analysis system was used to record 28 participants' double side kick execution. Fighters were divided into groups determined by their highest tournament achievements (national and international athletes). A comprehensive biomechanical model was developed expanding on an existing functional phase model solely derived from the kicking leg motion. Supporting leg and thorax motion phases were added. Appropriate variables were defined and obtained to characterise balance and sequential kick action. The statistical analysis established that (a) better techniques are characterised by less directly supported dynamic balance conditions and (b) there is a clear proximal-to-distal sequence (PDMS) for each kick movement, whereby better fighters create more hip-abduction angular change and higher angular velocities at PDMS1 and more angular velocity during the knee extension of the second PDMS. Results indicate that better fighters show a higher variety in dynamic balance conditions, as well as a stronger focus in the first leg abduction and their second leg extension.

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KEYWORDS
Sequential action; balance and stability; pointfighting martial arts; proximal-to-distal movement sequence; technique analysis; kinematics

1. Introduction

Sport biomechanics plays a vital role in performance improvement by directly contributing to the development of training practices, novel techniques as well as discipline-specific devices and technologies (Dabnichki, 1998). The influx of new urban sports (a substantial number of them stemming from traditional ones but with relaxed rules and regulations) provides an opportunity to analyse and develop novel efficient sport-specific techniques or to extract successful patterns from existing executions (Rinaldi et al., 2018). This tendency leads to less performance restrictions and provides opportunities for evolutionary technique development evident by the emergence of new styles outlined below.

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Supplemental data for this article can be accessed here

1.1. Pointfighting

Pointfighting Martial Arts, such as kickboxing, karate and sport karate, are defined by the 'Point-Stop'-scoring system, where only the first regular technique which reaches the opponent scores as a point (ISKA, 2016; WAKO, 2019; WKF, 2020). After a short point awarding break, the fight is resumed. The higher overall score determines the winner. The "first to touch" rule requires the fighters to be faster, so the opponent is reached before being able to counter the technique (Siska & Brodani, 2017). Consequently, one aim of these sports is to heavily reduce the duration between the first recognisable movement, to which an opponent is able to react, and the target contact of a technique execution (Hölbling et al., 2017). This is particularly difficult in complex techniques and combinations involving dynamic balance changes, such as kicks.

1.2. Martial arts kicking techniques

Martial Arts kicking techniques constitute highly complex serial tasks "consisting of a series of several distinct elements strung together to produce an integrated movement" (Kent, 2006). Therefore, superior Martial Arts techniques require a variety of skills, including inter-coordinated and -dependent series of sub-sequential elements based on impeccable dynamic balance combined with high power generation, executed with accuracy (Neto et al., 2013). In literature, sequential actions have been analysed only for single-leg techniques (Estevan et al., 2015; Jemili et al., 2017; Zago et al., 2015), with the exception of Hölbling et al. (2017) and a case study by Alsamad (2012) for multiple kicks. Functional phases are defined solely for the kicking leg's action (Quinzi et al., 2016). As stated above, successful kicking performance also requires that athletes maintain dynamic balance and stability. However, balance studies in fast sport movements involving single-leg slides (sliding or small jumping movements with the supporting leg, while the kicking leg is already elevated) are very complex. Therefore, balance analyses in Martial Arts are solely performed on hand techniques (Cesari & Bertucco, 2008; Gulledge & Dapena, 2008). High power generation relies on both muscular strength and well-coordinated sequential actions. With opto-electronic measuring systems a common way of analysis is by determining proximal-to-distal movement sequences (PDMS) that facilitate the transfer of momentum from larger to smaller segments of the kinematic chain to increase the velocity of the latter and ultimately the power output. Most power generation analyses focused on single movements (Ervilha et al., 2018; Kim et al., 2011; Pozo et al., 2011). PDMS has been successfully applied to Martial Arts punches (Fuchs et al., 2017) and rear-leg kicks (Kim et al., 2011; Sorensen et al., 1996) but surprisingly front-leg actions were never considered.

1.3. Martial arts combination (double side kick)

Modern disciplines often developed more dynamic techniques as a result of the freedom of action afforded by their respective codes. Competitors combine distance covering with repeated attacking kicks. The double side kick is normally started from a double foot support/jumping movement, called "bouncing" (Yuncza, 2011) or "hopping" (Young-Kwan & Yoon Hyuk, 2011), leading to a combination of two lateral front-leg kicks, without dropping down the leg (Figure 1(a)). The second kick aims to reach the target by using

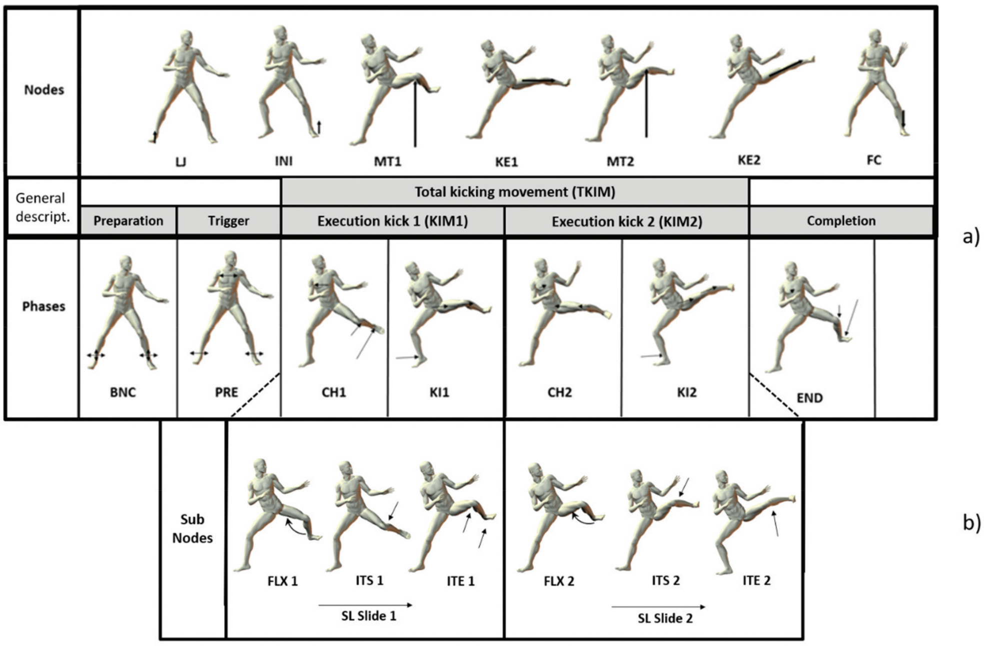

Figure 1. Phase separation of (Hölbling et al., 2017), with Sub Nodes and general movement description added.

a thrust movement with a 90° dorsal flexed ankle. It is a frequently used competition technique (Ouergui et al., 2013; Siska & Brodani, 2017), whereby the chambering position normally occurs between the two other lateral kicks (roundhouse and hook kick). Lateral kicks are notionally characterised by a main leg elevation movement projected on the coronal plane and a kicking movement projected on the transversal plane. Furthermore, only one study (Hölbling et al., 2017) relates the execution patterns to a potential success in a real fight. This study also facilitates a functional phase model of the kick. However, as stated above, the phases are solely based on the kicking leg, whereby other actions which are potentially important for balance or ultimately power generation are clearly neglected. Furthermore, previous studies failed to normalise sequence durations, which could result in bias and errors due to different anatomical attributes.

The aim of this study is to identify appropriate kinematic characteristics for the supporting leg (SL), kicking leg (KL), pelvis and thorax actions, as well as related dynamic body balance, which all contribute to superior performance. Based on existing research and extensive qualitative analysis it is hypothesised that overall

H1: The temporary characteristics (relative phase and subphase durations) of the double kick action differ significantly between national level and international elite fighters.

The second important area is related to the dynamic balance and stability of the athlete during the technique performance. Specifically, we hypothesise that proposed image-based measures for dynamic balance and stability can be used to distinguish between skill levels, resulting in two hypotheses:

H2.1: There are quantifiable, significant differences in the dynamic balance between national level and international elite fighters.

H2.2: There are quantifiable, significant differences in the dynamic stability between national level and international elite fighters.

Lastly, we hypothesis that there are clearly identifiable differences in the kinematic characteristics as expressed in the last two hypotheses.

H3.1: Angular change of PDMS of both kicking movements significantly differs between national level and international elite fighters.

and

H3.2: Angular rate of change significantly differs between national level and international elite fighters.

2. Materials and methods

2.1. Sample

The sample group consisted of 28 fighters from 7 countries (see Table 1). The athletes were divided into two groups based on their highest tournament accomplishment. The international (elite) group is formed by nine world- or continental championship finalists and five world-cup tournament winners. The national (level) group consists of fighters with at least 3 years of experience and four additionally won national championships in their respective country.

The study was approved by the ethics committee. All participants signed informed consent forms.

2.2. Kinematic data collection

The current research is conducted as a secondary study using raw data of Hölbling et al. (2017). All participants performed at least one trial of three consecutive double side kicks, with the second kick reaching the target (punching bag) with a thrust movement. They repeated these trials until personally satisfied with the execution. Thirty-nine markers were attached to their bodies following the "plug-in-gait" full-body model (Vicon®, 2010). Trials were recorded by eight infrared cameras positioned around the athlete and his

Table 1. Description of participants, by groups.

Groups	Age (years)	Mass (kg)	Height (m)	Leg length (m)	N
All	28.39	77.25	1.83	0.94	28
	±6.88	±7.79	±0.09	±0.05	
International	27.00	77.93	1.85*	0.94	14
	±5.14	±8.32	±0.09*	±0.05	
National	29.79	76.57	1.84	0.94	14
	±8.21	±7.48	±0.09	±0.06	

***Variable significant differs from normal distribution.**

target. The system set-up and the environment were specifically selected to reduce noise that affects the accuracy and reliability of the kinematic analysis (Dabnichki et al., 1997). An additional standard video camera (60 Hz) was used to simultaneously record the technique execution for monitoring.

2.3. Data processing

The markers' trajectories obtained via Vicon Nexus® at 250 Hz sampling rate were smoothed using the cross-validated quintic splines (Woltring, 1986) to ensure the accuracy and reliability of data. Additional anthropometric data was recorded and included in the program as "subject data", following the guidelines (Vicon®, 2010). Then, static and dynamic plug-in-gait models (Vicon®, 2010) were applied to the avatar (digitally connected trajectories), in order to calculate joint angles and centre of mass (COM) position. The trial with the highest horizontal peak velocity of the COM for each participating athlete was chosen for analysis.

2.4. Kick performance analysis

The study applied comprehensive analyses in the following order:

- Significant segments and joints were identified as a foundation for valid phase separation.
- On that basis, the extended phase model was established, using thorax (global angle), SL and KL (knee and hip joint) motion.
- Based on the above, specific thresholds for each identified motion were defined and applied to all athletes, for calculation of relative durations.
- A model is proposed for static and dynamic balance indication to identify specific characteristics.
- Analyses of sequential action and identification of PDMS were conducted.

Definitions of variables and their usage case are shown in appendix A.

2.4.1. Sequential action

The seven functional phases defined by the KL action from Hölbling et al. (2017), who only compared absolute durations (which is considered to be biased by the athletes' size, as, e.g., longer legs might lead to longer elevation duration) of their phase model, were used as the initial template for analysis of relative phase durations. Additional sub-nodes were then added based on the actions of the SL and thorax (see Figure 1 and Table A.1 for detailed descriptions). The duration between INI (start of the KL elevation) and KE 2 (end of TKIM) was taken for time normalisation (100%). The preceding (PRE) action is indicated with a negative sign, while post KE2 action is given as greater than 100%. Motion sequences were created parallel for the SL, the KL and the upper body using knee, hip, pelvis and thorax angles. An elite participant with representative but high-level movement patterns was chosen for the visualisation of an exemplary sequential action.

2.4.2. Balance and stability

To analyse balance and stability during TKIM without ground reaction force inputs (as this would need numerous force plates related to different slide distances) for the centre of pressure calculation, two parameters, as explained below, are proposed. Balance describes "the ability to maintain a stable and specific orientation in relation to the immediate environment" (Kent, 2006). As this definition implies, a closer horizontal distance between the area of support and the horizontal component of the COM might be beneficial for balance. Therefore, the BAL parameter is used as a balance indicator to assess relative distance between the projection of the COM on the ground and the minimum from the supporting foot or toe normalised by the respective COM height of the participant at that instance (z_{COM}).

$$BAL = \begin{cases} 0 & for \forall x_{COM} : (x_{COM} < x_{SLtoe}) \wedge (x_{COM} > x_{SLheel}) \\ \frac{1}{z_{COM}} \min(|x_{COM} - x_{SLtoe}|, |x_{COM} - x_{SLheel}|) & foranyotherconfiguration \end{cases}$$

Formula 1: Balance indicator

x = horizontal position in target direction
z = vertical position
SLtoe = Supporting leg toe marker
SLheel = Supporting leg heel marker
COM = Centre of mass

Stability is defined as the "tendency of an object to maintain its resting position or maintain a constant linear velocity or angular velocity" (Kent, 2006), whereas dynamic stability is defined as the "ability to maintain equilibrium while moving" (Kent, 2006). Therefore, in contrast to balance, stability is heavily affected by the height of an object (Kent, 2006). Thus, the stability indicator (STAB) is defined as the total relative distance between the base of support and the COM and is normalised respective z_{COM}.

$$STAB = \frac{1}{z_{COM}} \min\left(\sqrt{(|x_{(COM)} - x_{(SLToe)}|)^2 + (|z_{(COM)} - z_{(SLToe)}|)^2}, \sqrt{(|x_{(COM)} - x_{(SLHeel)}|)^2 + (|z_{(COM)} - z_{(SLHeel)}|)^2} \right)$$

Formula 2: Stability indicator

x = horizontal position in target direction
z = vertical position
SLtoe = Supporting leg toe marker
SLheel = Supporting leg heel marker
COM = Centre of mass

The two parameters allow for a more precise image-based estimate of the participant's balance.

2.4.3. Power generation

To identify PDMS starting with the pelvis tilt (global angle) as the most proximal segment contributing to the final power output, further distal joint angles (hip abduction and knee extension) were chosen for analysis. Additionally, the maximum rate of change of all PDMS angles and the horizontal velocity of the KL foot (pulse transmission segment) were used to assess movement differences between skill levels.

2.5. Statistical analysis

Statistical analysis was performed using SPSS ver. 22 (IBM Corp., Chicago, Illinois). All variables were checked for normal distribution using Shapiro–Wilk test as dictated by the sample size of <50 participants with the significance level p=0.05. Mean values and standard deviation or median and inter-quartile range for variables differing significantly from normal distribution were obtained for each participant and each group. T-tests for independent samples were performed to identify significant differences for all relative phase and sub-phase durations, stability and balance variables, angular ranges, and angular rates of change for both PDMS. Mann–Whitney U-test was used if the requirements for the t-test were not satisfied.

3. Results

General movement description (see supplemental material video and appendix B):

The PRE phase (rel. duration: 55.29% ± 12.04) contains different movement combinations, which may support the initiation of the SL slide1. The phase begins at the start of the last bounce and ends with the KL foot elevation, which marks the beginning of CH1 (relative duration: 38.95% ± 5.35). The SL knee is still extending, while the SL hip joint becomes flexed (in an already abducted position), so PT (pelvis tilt) can be performed marking the first part of the PDMS. Simultaneously, KL's hip and knee joint is flexed to reduce the lever arm for the pendulum-like leg elevation initiated by KL hip abduction as the second part of the PDMS. Approximately at the end (marked by maximum knee flexion angle) of the KL knee flexion (10.94% ± 3.45 before KE1) the KL elevation decelerates by more than 9.81 m/s^2 (marks ITS and ends with ITE). The slide (marked by horizontal SL toe velocity >100 mm/s) contains a SL knee and hip flexion, followed by a SL hip extension to close the distance to the target. During this deceleration, the KL hip and knee extensions start, marking the third part of the PDMS, entering KI1 (relative duration 7.69% ± 3.00). This phase ends with KE1, while the SL is still sliding for all but four participants.

The SL slide1 ends after 30.89% ± 3.42, which is approximately the mid of CH2 for most participants. Meanwhile, KL hip and knee are flexing again starting the next PDMS with the same sequence as above (PT-hip abduction-FEXT (hip and knee/full extension)). The leg elevation provides another higher-than-gravity deceleration at its end. Simultaneously, after slide1, the SL knee (still flexed) is extended again to initiate a thrust movement for a second slide (all but three participants) ending at KE2. The PDMS is characterised by the generation of additional force through the initiation of centrifugal acceleration of the pendulum-like leg elevation. This in turn leads to the velocity of the KL foot being lower (7.4 m/s ± 0.1).

As described above, the model of Hölbling et al. (2017) was enhanced by adding 8 subnodes based on kick leg, supporting leg and thorax movement, i.e.

- Maximum knee flexion (FLX1 & FLX2) for both kicking movements;
- Two supporting leg slides (Slide1 & 2);

- Start and end of the impulse transfer between the kicking leg abduction to the centre of mass (ITS & ITE 1&2).

Significant differences were only found for the phases CH1 and KI1. Detailed results of t-tests and Mann–Whitney U-tests are presented in Table 2a, while descriptive statistics are shown in appendix C (a).

Results for balance (BAL) and stability (STAB) indicator show significant differences at BAL: KE1 and STAB: KE1; KE2 and max between groups. All other results are presented in Table 2b and descriptive statistics in appendix C (b).

Proximal-to-distal movement sequences analyses in terms of angular change at the first hip abduction (Hip1) and knee flexion (Knee1), as well as angular velocity at Hip1 and second knee extension (Knee2) showed significant differences. Further results to PDMS are presented in Table 2c and appendix C (c).

4. Discussion

4.1. Kick movement description and relative phase coordination

Fast and complex sport movements comprise a multitude of different motions, each contributing to the final technique goal. The newly introduced sub-nodes illustrated in Figure 1 and described in appendix B allowed for a better understanding of different contributing factors to superior technique performance. A timeline illustration of a representative high-level double side kick action is provided in Figure 2. Analysis of the relative phase and sub-phase durations showed that there are significant differences between the skill groups in the durations of the first chambering phase (longer for better fighters), the first kick phase (shorter for better fighters). Hypothesis 1 can therefore be accepted in terms of the identified phases. Findings suggest that sub-phase differences are too small to result in significant differences with this sample size, even though descriptive statistics hint further differences at, i.e. KLdec1 (Appendix Ca). Therefore, it is not clear if these phases contribute to overall performance, but they are believed to pose important elements for comprehensive technique understanding.

4.2. Relative COM position and projection (BAL & STAB)

It is noted that the proposed balance (BAL) and stability (STAB) measures do not present absolute calculations of balance and stability but rather constitute indicators for comparison between athletes. Specifically, they have proved useful quantitative parameters to assess the technique performance. This is strongly underlined by the fact that both parameters distinguish different skill levels in certain movement sequences. Generally, a higher value in both variables indicates a less stable condition as the distance between COM and COP at single leg support is higher. Better fighters show the ability to perform the technique under less stable conditions at the first knee extension (BAL & STAB KE1), the second knee extension (STAB KE2) and their maximum condition ($STAB_{max}$). In particular, hypothesis 2.1 is accepted in terms of the first knee extension (KE1) nodes. Whereas, hypothesis 2.2 is specifically valid for the first & second knee extension and the

Table 2. Analysis of group differences using t-test for independent samples and Mann–Whitney U-test if the requirements for t-test were not met.

a) Phase and subphase durations

	Relative phase durations						Relative subphase durations						
	PRE	CH1	KI1*	CH2	KI2	END	FEXT1	FEXT2	Slide1	Slide2*	KLdec1*	KLdec2	Thorax r
Diff.	5.70	4.82	-2.68	-1.44	-1.17	2.43	-0.29	-0.53	1.72	-3.35	5.15	2.43	2.32
p	0.21	0.02	0.02	0.49	0.43	0.47	0.83	0.70	0.19	0.38	0.78	0.49	0.69

b) Stability and balance

	Balance analysis					Stability analysis						
	BAL INI	BAL KE1	BAL KE2	BAL max*	BAL min	STAB INI*	STAB KE1	STAB KE2	STAB max	STAB min*	Slide 1	Slide 2
Diff.	-5.97	25.20	1.31	5.69	1.63	0.46	5.29	2.26	2.44	0.91	47.14	-62.29
p	0.09	>0.01	0.67	0.14	0.56	0.82	0.03	0.03	>0.01	0.18	0.28	0.31

c) PDMS

	Angular changes of both PDMS						Angular velocities and foot velocities of both PDMS							
	Pelvis1*	Hip1	Knee1	Pelvis2*	Hip2*	Knee2	Pelvis1*	Hip1	Knee1	Foot1	Pelvis2*	Hip2*	Knee2	Foot2
Diff.	3.86	12.77	-16.62	-3.43	-1.10	10.13	52.6	61.81	16.08	185.68	21.65	-9.7	215.24	259.00
p	0.11	>0.01	0.03	0.52	0.46	0.17	0.43	0.01	0.85	0.65	0.38	0.43	0.03	0.59

* Variable significant differing from normal distribution.

$^{+}$Significant difference between groups.

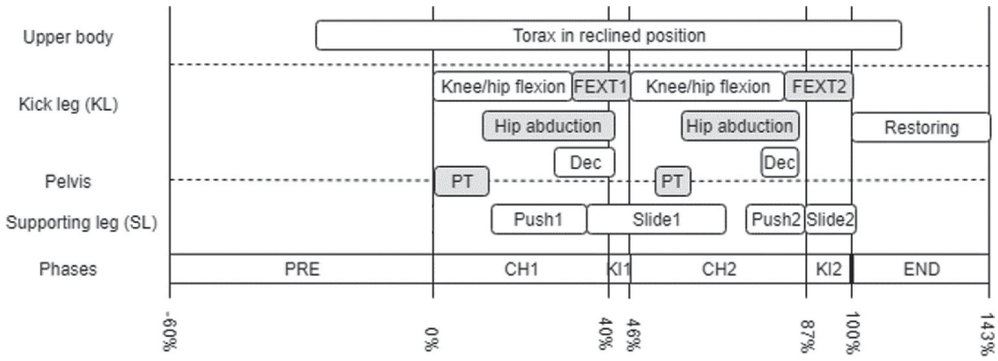

Figure 2. Schematic illustration of sequential action of the main double side kick motions of a representative top 5 participant. The proximal to distal impulse transfers are marked in grey. KIM=Kick motion; PT=Pelvis tilt; Push=SL knee and hip extension; Dec=Deceleration of KL abduction (higher than gravitational acceleration).

maximum (max) value. However, descriptive statistics from appendix C(b) indicate potential differences also for other phases, such as $BAL_{INI,}$ BAL_{max}, Slide1 and Slide2.

4.3. Kicking power generation (PDMS)

The sidekicks' PDMS are characterised by pulse transmission from the pelvis tilt over the hip abduction to the full leg extension. Compared to other PDMS observations that are limited in one movement direction, the generation of additional force for the side kick is performed through the initiation of the pendulum-like pelvis and leg elevation and indirectly continues as centrifugal acceleration of the KL full extension. Based thereon, resulting KL foot velocity is lower (7.5 m/s) compared to studies on roundhouse kicks (14.7 m/s), where PDMS is characterised by direct pulse transmission (Kim et al., 2011).

Angular change as parameter for movement range is significantly higher within the first hip abduction (Hip1) and significantly lower in the first knee extension (Knee1) for better fighters. Therefore, Hypothesis 3.1 is accepted for these phases, whereas the angular velocities are significantly higher for Hip1 as well as second knee extension (Knee2) for better fighters, allowing us to also accept H3.2 for the respective parts of the PDMS. These results combined indicate that better fighters are elevating their leg higher and faster already prior to their first kick and extend their leg faster for the second kick. Therefore, it can be stated that the focus of the first kick relies on the leg elevation and the second on the leg extension.

Summarised, the findings indicate that

- fighters at different skill levels can be best distinguished by their first leg elevation performance and second extension movement.
- better ranked fighters show more balance and stability variation, increasing their ability to move towards the opponent, while elevating their legs very high.

- the main focus in power generation for the first kick relies on the vertical movement (leg elevation), whereby the aim of the second kick is to generate speed in horizontal direction (leg extension; kicking thrust movement).
- flexibility and strength in hip abduction are crucial for a successful performance as better fighters abduct their KL hip stronger to gain kicking height.

4.4. Implications

The temporary and kinematic parameters identified in this study allow for easier purely image-based assessment of the relative skill level of the fighters' execution of the considered technique. It is also clear how certain parts of the action could be targeted to improve the overall performance.

This analysis has several highly important practical implications for Martial Arts kicking techniques. As stated above, the first kicking movement is predominantly used to facilitate sufficient leg elevation, as the first hip abduction is higher and faster for better executions and the average hip abduction movement range is about 3 –5 times higher than the second one for all groups (see, Appendix Cc). However, the knee extension and the vertical foot velocity are higher for the second kick, indicating a focus on kick impact for the second kick (see, Appendix Cc). Based on the higher leg elevation and the following vertical deceleration, which consequently lifts the COM as unweighting movement (Müller, 1994), the normalised first slide distance is in average about 3-5 times longer than the second (see, Appendix Cb).

As the leg elevation is dependent on more physical and coordinative abilities (hip joint flexibility; strength of smaller and less used muscles and dynamic balance) than leg extension, skill groups are easier to distinguish within the first kick phase.

4.5. Limitations

The skill of a fighter in this paper is defined by overall competition performance; however, it is noted that this includes other factors but solely the kicking performance, such as hand technique and tactical skills. Therefore, an additional performance parameter focusing only on kick performance could offer a sharper line between athletes' skill levels.

The methods for balance and stability indication introduced in this paper seem to be adequate for this analysis, even though measuring the exact centre of pressure with a force measuring mat could lead to more detailed results for stability and balance analysis, as well as build the basis for full balance calculations.

Furthermore, future studies should include kick impact analysis to link power generation to the final kicking force output.

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Declaration of interests

The authors declare that there is no conflict of interest.

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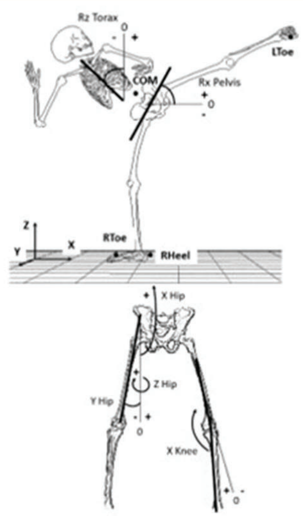
Appendices

Appendix A: Variable definition. Exact marker placement and model calculations in Vicon® (2010).

Variable		Usage	Description	Image
COM	(x)	Trial selection/BAL	Horizontal component of the COM	
	(z)	STAB	Vertical component of the COM	
Foot marker	Heel (x)	STAB/BAL	Horizontal component of the heel marker	
	Heel (z)	STAB/BAL	Vertical component of the toe marker	
	Toe (x)	STAB/BAL/Slide	Horizontal component of the toe marker	
	Toe (z)	STAB/BAL/Slide	Vertical component of the toe marker	
Thorax angle	(rz)	Thorax recline	Global angle of the thorax in relation to the systems' origin; axis goes through the middle between the marker on cervical vertebrae 7 (C7)/ clavicula (CLAV) and thoracic vertebrae 10 (T10)/ sternum (STERN)	
Pelvis angle	(rx)	PDMS	Global angle of the pelvis in relation to the systems' origin; axis goes through left and right hip joint centre, with iliac anterior superior markers as origins.	
Hip angles	Flexion (x)	FLX	Leg elevation angle on the sagittal plane	
	Abduction (y)	ITS&ITE/PDMS	Leg elevation angle on the coronal plane	
		-	hip joint centres are defined between calculated pelvis axis and the calculated femur axis, which ends in the knee joint centre	
Knee angle	Flexion (x)	FLX	Lower leg elevation on the sagittal plane; Leg flexion. the knee joint centre is calculated using a modified chord function and the hip joint centre with knee and thigh (THI) marker	

5

[5] Due to a publication editing format error (figures were misplaced), which has already been submitted to editing service of the Journal, this page had to be corrected.

Appendix B: Phase separation, based on and extended of Hölbling et al. (2017).

	Phases		Nodes		Subnodes	
	Name	Description	Name	Description	Name	Description
	BNC	Bouncing: ighting movement	LJ	End of the BNC phase: 1st floor contact of the SL before the kick preparation		
	PRE	Preparation phase: last bounce before the kick, includes most initial movements and telegraphs	INI	End of the PRE phase: last floor contact of the KL before elevation		
100%	CH1	First chambering phase: includes KL flexion and elevation	MT1	End of the CH1 phase: Defined by the highest elevation of the KL knee at an angle of max. 110 degrees (rounded and averaged half of the extension angle change; see Hölbling et al., 2016)	FLX1 Slide1 ITS1	Knee flexion1: maximum flexion of the KL knee during the CH1 phase and start of the full extension movement FEXT1 Start and end of the first slide Impulse transfer start 1: Start of the -higher than gravitational acceleration- deceleration of the KL abduction movement
	KI1	First kicking phase: remaining kicking movement after the full leg elevation	KE1	End of the KI1 phase: maximum extension of the KL knee	ITE1	Impulse transfer end 1: end of the -higher than gravitational acceleration- deceleration of the KL abduction movement. Can also be in CH1
	CH2	Re-chambering phase: includes KL flexion and elevation	MT2	End of the CH2 phase: defined by the highest elevation of the KL knee at an angle of max. 110 degrees (rounded and averaged half of the extension angle change; see Hölbling et al., 2016)	FLX2 Slide2 ITS2	Knee flexion1: Maximum flexion of the KL knee during the CH1 phase and start of the full extension movement FEXT2 Start and end of the first slide Impulse transfer start 2: Start of the -higher than gravitational acceleration- deceleration of the KL abduction movement
	KI2	Second kicking phase: remaining kicking movement after the full leg elevation, end of the kick	KE2	End of the KI2 phase: maximum extension of the KL knee	ITE2	Impulse transfer end 2: nd of the -higher than gravitational acceleration- deceleration of the KL abduction movement. Can also be in CH2
	END	Completion of the technique by restoring the KL to the floor	FC	First floor contact of the KL foot		

Appendix C: Descriptive statistics

a) Phase and subphase durations

	Mean normalised phase durations (%)						Mean normalised subphase durations (%)						
Groups	PRE	CH1	KI1	CH2	KI2	END	FEXT1	FEXT2	Slide1	Slide2	KL dec1	KL dec2	Thorax rec
All	55.29	38.95	7.69*	36.77	15.94	58.60	10.94	27.69	30.89	14.35*	14.49*	12.35*	169.23
	±12.04	±5.35	±3.00	±5.35	±3.86	±8.80	±3.45	±3.59	±3.42	±11.00	±11.00	±8.00	±14.52
International	58.48	41.20	6.70*	36.24	15.34	60.09	10.89	27.47	31.78	13.35	18.16	11.31*	170.43
	±12.16	±4.33	±2.00	±5.22	±4.01	±8.17	±4.09	±3.03	±3.92	±9.25	±5.95	±13.00	±13.83
National	52.33	36.86	9.38	37.27	16.50	57.22	10.95	27.89	30.06	16.70	13.00*	11.73	168.11
	±11.56	±5.50	±2.80	±5.61	±3.78	±9.44	±2.88	±4.16	±2.77	±11.16	±10.00	±5.61	±15.57

b) Balance and Stability

	Mean normalised BAL at different nodes (%)					Mean normalised balance indicators (%)					Mean absolute distance (mm)	
Groups	BAL INI	BAL KE1	BAL KE2	BAL max	BAL min	STAB INI	STAB KE1	STAB KE2	STAB max	STAB min	Slide1	Slide2
All	15.24	7.47	-8.63	33.86	-24.64	52.21*	58.91	55.50	61.99	50.99	960.49	219.25
	±8.74	±18.73	±8.09	±9.82	±7.54	±3.00	±3.62	±2.83	±2.40	±1.74	±111.08	±162.21
International	12.72	21.61	-7.99	38.69*	-23.92	53.04	61.74	56.75	63.24	51.44	991.56	186.02
	±8.42	±8.45	±6.35	±12.00	±5.93	±2.92	±2.46	±2.83	±2.56	±2.09	±109.63	±140.62
National	17.37	-3.19	-8.86	33.10	-25.74	52.58	56.65	54.41	60.90	50.53	912.54*	245.91
	±8.06	±17.49	±9.51	±6.36	±8.53	±1.70	±2.58	±2.23	±1.67	±1.05	±130.00	±176.66

c) PDMS

	Angular Change (°)						Angular rate of change (°/s)			Vel. (mm/s)	Angular rate of change (°/s)			Vel. (mm/s)
Groups	Pelvis1	Hip1	Knee1	Pelvis2	Hip2	Knee2	Pelvis1	Hip1	Knee1	Foot1	Pelvis2	Hip2	Knee2	Foot2
All	26.94*	31.01	76.37	15.69*	7.43*	113.42	159.34*	252.37	978.35	6942.69	141.53*	199.69*	1326.79	7358.04
	±10.83	±10.45	±20.41	±9.49	±8.10	±19.14	±62.70	±64.99	±224.26	±1057.02	±82.95	±159.50	±270.57	±1249.40
International	28.08*	37.39	68.05	13.46*	7.93	118.49	209.09	283.27	989.39	7035.53	123.74*	191.34	1434.41	7487.52
	±6.60	±7.57	±20.37	±7.44	±4.87	±18.00	±116.79	±48.79	±271.65	±1022.83	±91.44	±86.61	±244.36	±1346.91
National	24.22	24.62	84.68	16.89	9.03	108.36	156.49	221.46	970.31	6849.85	145.39*	201.04*	1219.17	7228.54
	±14.16	±9.03	±17.35	±15.07	±9.90	±19.54	±87.07	±65.83	±174.70	±1120.62	±82.99	±184.36	±259.60	±1179.75

*Variable significant differing from normal distribution

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Exploration of Martial Arts Kick Initiation Actions and Telegraphs

Original Manuscript

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Abstract

In Martial Arts a technique can be identified by its preceding actions. These initiation actions can be detected by the opponent to initiate counterattacks. For kicks, fighters perform preceding actions to generate balance and ease leg elevation or follow up movements. The aim of this study is to define these movements using a large sample with different skill levels (advanced to world leading) and compare different movements by duration and motion amplitude. The kick preceding actions and regular fighting movements (from beginning until 2 bounces prior to leg elevation) of a kicking combination performed by 44 fighters were analysed via Vicon® motion capturing. Initiation action start was determined by the moment during the preparatory phase, when a joint angle significantly exceeds or subceeds a specific threshold (3Sd). Descriptive statistics and qualitative analysis were used to summarize movement types, durations and amplitudes. T-test, Wilcoxon test and Friedman test (with Bonferroni-Dunn test as post hoc) were performed to analyse differences of durations and motion amplitudes between different groups of variables. Outcomes suggest that initiation actions contributed to weight redistribution happen earlier and are smaller than ones contributed to centre of mass elevation.

Keywords: Sequential action; Initial movements; Telegraphs; Martial Arts; Technique analysis; Kinematics

1. Introduction

Sports movements, particularly regarding performance development, are exceptionally complex. Especially in Martial Art, like kickboxing and karate, where sportive success is not solely determined by single, mostly physical output factors, like running speed or throwing distance, a huge number of influencing factors must be taken into consideration, when it comes to distinguishing the quality of performances. Close distances and fast motions make it very difficult to counteract or even avoid techniques, which is essential for both injury prevention and winning.

Previous research concluded that the time period between the start of a technique and a potential strike is even shorter than minimum reaction time of the opponent, especially including the amount of time necessary for performing an escape or even counterattack action. Mori et al. (2002) for example stated that complex (choice) reaction time (on videos with 2 different techniques) of karate athletes is about 500-600ms, whereas execution times of simple techniques are between 9-15ms (punch to the head of Olympia boxers), according to Walilko et al. (2005) and complex techniques such as a roundhouse kick about 260ms (Kim et al., 2011). However, as sports practice shows it is possible to counterattack even very fast techniques from a short distance. Consequently, the athletes are able to anticipate on motions or situational probability prior the start of the technique itself (Milazzo, Farrow, Ruffault, et al., 2016; Mori et al., 2002). The importance of disguising for successfully outwitting the opponent is also well known in tennis lob (Shim et al., 2005) and football penalty kick (Savelsbergh et al., 2002).

However, several studies on reaction or execution time reported the respective segment (punch-hand or kick-foot) as beginning of their count (C. Falco et al., 2011; Petri, Emmermacher, et al., 2019; Petri, Masik, et al., 2019), whereas other research suggests a more proximal focus, such as knee (Mudric et al., 2015), pelvis (Vieten et al., 2007) and centre of mass (Milazzo, Farrow, Ruffault, et al., 2016). In contradiction several kinematic studies on kicking techniques describe maybe even earlier initiation actions for kicking techniques. Wąsik (2011) for example describes the lateral front-leg kick initiation as shifting the supporting leg in front of the kicking leg, whereas Yuncza (2011) and Witte et al. (2007) call it ‘closing step’. Another, noticeable movement is the Muay Thai “switch stance” (Turner, 2009). In sports practice, these “early cues” (Petri et al., 2017) are also known as “Telegraphs” (TGs), describing movements or initiation actions prior the actual technique start (e.g. leg elevation), which are large enough to be potentially detected and identified by the opponent. In the example of Wąsik (2011), the “shifting the back leg forward” TG starts about 400ms before the kicking leg elevation, which is about 2/3 of the duration, the kick itself takes (0.62s). This makes it essential for athletes to avoid these TGs and for opponents to detect them and anticipate. On the other hand, subtle initial movements might be mechanically beneficial as for example counter movements can increase the cumulated power output of a technique (e.g. comparison counter movement and static jump exercise). Furthermore, an adaption of the area support can improve the dynamic balance (Hölbling et al., 2020), particularly for kicking movements. Both leads to the assumptions that initial movements cannot or should not be fully eliminated as they help facilitating optimal starting conditions regarding biomechanical aspects (Hochmuth, 1984). Based on qualitative analysis, the kick initiation actions might actually comprise 2 different types of biomechanical functions. Firstly, a change of the supporting conditions from double- to single-foot support (WRT: Weight Redistribution Telegraphs). These and similar movements are effectively changing the weight distribution in order to ultimately increase the power output. Secondly, an up- unweighting (Müller, 1994) function to ease the distance reduction to the target and support the leg elevation (CET= Centre of mass Elevation Telegraph). Both functions are also used later, during the subsequent kicking motion in complex techniques (Hölbling et al., 2020). Consequently, this amounts to a compromise between power generation, balance and avoidance of treacherous movements or in other words to perform initial movements subtle enough to not get TGs.

Therefore, several studies analysed the gaze and visual search behaviour of fighters reacting on attacks of real, videoed or animated opponents (De Quel & Bennett, 2019). While most authors found differences between novices and experts (Lee et al., 2010; Ripoll et al., 1995), the gaze fixations differ widely. Milazzo, Farrow, and Fournier (2016) and Williams and Elliott (1999) found that karate athletes focus their gaze on head and chest, while Lee et al. (2010) states gaze of their taekwondo athletes is on trunk or legs. Furthermore, Hausegger et al. (2019) found that, peripheral vision must also play an important role.

In summary, there is a substantial volume of research on reaction times and gaze, however, it is not yet known, which variety of movements are performed prior kick executions. Furthermore, most mentioned studies use rather simple kicking techniques (Mudric et al., 2015) performed in a static position (Coral Falco et al., 2009), while most sports use fighting movements, such as ‘bouncing’ (Yuncza, 2011) or ‘hopping’ (Young-Kwan & Yoon Hyuk, 2011) as preceding movements. Furthermore, most studies only comprise small samples (Mori et al., 2002) of attacking athletes. All of it, decreases the variety of initial movements and potential TGs. However, besides the enhancement of respective research (especially regarding peripheral vision), particularly athletes and coaches would benefit from substantial knowledge about initiation action and TGs.

To partially fill the research gap between technique execution and visual perception, it is stated that a complex, frequently-used kicking technique (Ouergui et al., 2013; Siska & Brodani, 2017), such as the double side kick, should be analysed. The technique consists of a series of 2 front leg side kicks, whereby the second one reaches the target. The kick combination is normally started from a double foot support/jumping movement, called bouncing (BNC phase), which can be described as an individual preceding fighting movement, which guarantees close to real-live results. Tis phase ends at the beginning (Node: LJ) of the final bounce (PRE phase, where according to Hölbling et al. (2017) all initiation actions are expected). After PRE at the node INI, the front leg is elevated and chambered (hip and knee flexion as well as hip abduction; Node MT1) followed by a thrust movement of the leg with a 90° dorsal flexed ankle. Without dropping the kicking leg, it is re-chambered and re-extended for the second kick, which reaches the target.

[Figure 1 near here]

As stated above, besides the technique complexity, the analysis needs to be conducted on a large sample with different skill levels, to gain a sufficient variety of execution patterns. It would also be beneficial to analyse Martial Arts disciplines in which rules are demanding that even little mistakes can lead to relatively high drawbacks. Pointfighting Martial Arts, such as kickboxing (WAKO, 2020), karate (WKF, 2020) and sport karate (ISKA, 2016), are defined by the 'Point-Stop' scoring system, where only the first regular technique which reaches the opponent scores as a point, which renders them ideal for TG analysis. Particularly, compared to other continuous disciplines like boxing or MMA, where follow up techniques are scored too.

The aim of this explorative study is to detect TGs by comparing angular ranges from PRE phase with BNC phase and define type and amplitude of initiation actions. Therefore, we hypothesised that:

1. There are significant deviations (>3Sd) between the angular range of all major joints (shoulders, elbows, hips, knees) and (global) segments (thorax, pelvis) during the

regular fighting movement (BNC phase) and the preparation phase PRE, which indicate a Telegraph.

2. There are significant differences of the relative start of the initiation action between different joints and segments as well as between the types of Telegraphs (WRT & CET).
3. There are significant differences in the joint or segmental angular movement amplitude between different initiation actions as well as between the types of Telegraphs (WRT & CET)

2. Materials and Methods

2.1 Sample

A sample of 44 fighters from 7 countries was chosen due to their best tournament achievement (10 world- and continental championship finalists; 11 world cup tournament winners; 8 national champions; 15 fighters with no noteworthy tournament success but at least 3 years of consistent training) to display a large variety of skill levels.

The study was approved by the ethics committee of university[1]. All participants signed informed consent forms.

2.2 Kinematic data collection

The current research is conducted as a secondary study using previously recorded raw data. Athletes performed at least 1 trial consisting of 3 executions of the respective competition technique. A maximum of trials was not defined. 39 markers attached to their bodies following the 'plug-in-gait' full body model (Vicon®, 2010) were recorded by 8 infrared cameras at 250 Hz, processed via Vicon® Nexus and digitalised as trajectories. The set-up was optimized by positioning the cameras in a way that markers are continuously visible to as many cameras as possible in order to reduce noise that affects the accuracy and reliability of the kinematic analysis (Dabnichki et al., 1997). An additional standard video camera (60 Hz) was used to record the technique execution from a normal (90°) perspective to movement direction for a qualitative evaluation of the techniques' success.

2.3 Data processing

Marker trajectories were smoothed using cross-validated quintic splines (Woltring, 1986) to reduce noise and ensure the accuracy and reliability of the following procedures. Static and dynamic plug in gait models (Vicon®, 2010) were applied to the digitally connected trajectories. The trial with the highest horizontal peak velocity of the centre of mass (COM) for each participating athlete was chosen for analysis.

2.4 Functional phase separation

The complex technique was divided into functional phases and reduced to the preparation (PRE) and the first chambering (CH1) phase defined by Hölbling et al. (2017) for analysis. The preceding (PRE) action is given as absolute value (in seconds) indicated with negative sign before the start of the leg elevation (Node: INI).

2.5 Initial movements and Telegraphs

As stated above the initiation of kicking techniques are characterised by weight redistribution or COM elevating movements, which possibly alert opponents and effectively increase their time to react. In Pointfighting Martial Arts, these motions are performed during the last bounce before the kicking leg elevation (Hölbling et al., 2017), which means a Telegraph consists of significant change of the segmental position within the PRE phase than the regular movement within the BNC phase. Therefore, a threshold was calculated to distinguish movements, which could be detected as Telegraphs from smaller motions. Based on an explorative try and error approach, with visual alignment and assessment of realistic delimitation by the researchers, it was decided to use the respective angle at the LJ node with 3 times standard deviation of the same angle during the BNC phase ($\text{Telegraph}_i = \varphi_{i(PRE)} > \varphi_{i(LJ)} \pm 3Sd_{\varphi i(BNC)}$) as threshold.

As soon as a TG was detected the start of the underlying initiation action was defined as the first frame of the continued increase/decrease before the threshold was exceeded. Furthermore, the movement range of this initiation action was calculated. Thereby, it was differentiated between WRT and CET. WRT amplitude, as it is used for a redistribution before the leg elevation is calculated by maximum minus minimum angle during the PRE phases. Whereas, CET range, as used to elevate the COM for the distance reduction to the target was calculated by maximum – minimum during PRE and CH1 phase (where a supporting leg slide movement starts; see Figure 1) of the kick. When several Telegraphs between a group (arms, torso, hips, knees, COM; WRT, CET) were detected, the average of starting times or movement amplitude was calculated, to avoid bias due to different numbers of observed angles via group. As a result of angular changes in the hip joints, foot movements occurred. These movements were classified into groups and quantified based on qualitative analysis of the researcher.

2.6 Statistical Analysis

Data was extracted from the Vicon® c3d files via a specially developed Python® data analysis routine and exported into Microsoft excel for further editing. All statistics were performed using SPSS ver. 22 (IBM Corp., Chicago, Illinois). Variables were checked for normal distribution using Shapiro-Wilk test as dictated by the sample size of <50 participants with the significance level p=0.05. Mean values and standard deviation (Sd) or median and interquartile range (IQR) for variables differing significantly from normal distribution were obtained. Differences between WRT and CET average start and amplitude were analysed using a t-test for repeated samples (or a Wilcoxon test for variables, which significantly differ from normal distribution). Average start and amplitude of variable groups, which were cumulated based on their segments (arms, torso, COM, hips, knees) were compared using the Friedman test, due to significant differences from normal distribution (for some variables). A Dunn-Bonferroni test was used to as post-hoc test du determine between-subject effects.

3 Results

In total 2 segments (thorax, pelvis) and 8 joints (shoulders, elbows, hips and knees) or combined 18 angles (thorax and pelvis tilt; knee and elbow flexion/extension; shoulder and hip flexion/extension, adduction/abduction and ext./int. rotation) were examined for Telegraph detection.

The percentage of athletes performing a specific group of telegraphs is shown in Figure 2A. Average start and amplitude of each initiation action is shown in Figure 2B&C.

[Figure 2 near here]

Inferential statistical analysis showed significant differences in both the average motion start (Δt) and the motion amplitude (φ) between WRT and CET (**Table 1**A). Furthermore, there were significant differences in Δt and φ between the grouping via segments (**Table 1**B), as well as several significant between-subject differences (**Table 1**C&D).

[Table 1 near here]

Qualitative analysis of foot movement is described in Figure 2D. The different movements can be described as follows:

1) SL closing bounce: During the last bounce, the supporting foot is positioned closer to the kicking foot (most likely under the centre of mass).
2) SL jump-in: No full bounce is performed as the kicking foot stays on the ground (and may be charged with most of the body weight), while the supporting leg is positioned closer to the kicking foot.
3) Double closing bounce: Both feet are moving towards each other, during the last bounce.
4) Double bounce forward: Both feet are shifted forward during the last bounce, while the distance between them, does not change significantly. Furthermore, it is noted that the participant did not touch the ground with the kicking foot again before leg elevation.
5) SL rotation: The supporting leg is rotated, so the foot faces in opposing direction of the target. It is noted that most participants performed an SL rotation but just 2 did not execute movement 1-4 too, which has a higher amplitude and starts earlier.

4 Discussion

In contrast to athletics and many other sports, the start of an action in contact sports is decided by the athletes, based on their judgement for a potentially successful outcome, which depends on the level of anticipation and preparation of the opposing side.

4.2 Telegraphs (TGs)

Telegraphs as defined above are initiation actions, which must deviate enough from regular fighting movement to be detectable by the opponent. Using the defined threshold (3Sd) all assessed joints and segments as well as the COM, showed several TGs throughout the sample, which clearly leads to the acceptance of hypothesis 1. However, solely the back-shoulder threshold was exceeded or subceeded by all participants, during the PRE phase and therefore, was a TG for all participants. It is further noted that all participants performed an individual sequence of TGs. Furthermore, 98% of participants performed a weight redistribution TG (WRT) and 93% used a TG for elevating the COM (CET), shown in Figure 2. Thereof, 93% performed hip, 89% arm, 68% knee, 59% torso and 27% COM TGs (Figure 2A). Hip TGs can be further described by their resulting foot movement. 21 participants in total (41% SL closing bounce and 7% SL jump-in), performed the "bounce fighting movement" -equivalent to the "shifting forward the back leg" movement described by Wąsik (2011) and other authors, while 17 (39%) bounced together with both feet. Furthermore, 2 participants just performed a SL rotation and 1 executed a very unique style (bounce forward with both feet), while only 3 participants did nonapplicable foot movement, according to qualitative analysis. This is supported by the results of hip joint telegraphs. However, we were not able to cluster the sequence of hip Telegraphs to the type of the foot movement, as a variety of variables might affect that.

4.3 Initiation action timing

Results indicate that the initiation actions of WRTs start significantly earlier than CETs (**Table 1**A), as well as between the segmental TGs (**Table 1**B), which leads to the acceptance of hypothesis 2. In accordance to Milazzo, Farrow, Ruffault, et al. (2016) and Vieten et al. (2007), post-hoc tests suggest that proximal initiation actions are starting earlier than distal ones, which also explains why more successful athletes tend to focus more on those (Lee et al., 2010; Ripoll et al., 1995). More precisely the average sequence can be illustrated as [COM; torso; hips > arms; knees], however, no significant differences between hip and arm were found (**Table 1**C). Given the average duration of a double side kick of about 0.74s (Hölbling et al., 2017) from INI to the second kick, it is stated that athletes who are able to detect WRT have about 33% and CET have about 25% more time to react, than athletes who focus on the leg elevation as first movement. Using the duration from INI to the first kick execution (about 0.34s in average) as reference, it is as much as about 73% for WRT and about 56% for CET.

4.4 Initiation action movement size

Mean motion amplitude of WRTs (37° ±17) were significantly smaller than CETs (103° ±56) and there were significant differences between the mean segment amplitudes (**Table 1**D), which leads to the acceptance of hypothesis 3. The sizes of the motion amplitudes could also be illustrated as [arms> hips; knees >torso]. This might also explain why less experienced fighters focus their gaze on distal segments, as they are easier to detect because of higher motion amplitude (Lee et al., 2010; Ripoll et al., 1995).

4.5 Combined implications

Results suggest that athletes should focus on detecting and avoiding WRTs, as they are performed (slightly) more often and start earlier than CETs. However, as their motion amplitudes are significantly smaller, they might be harder to detect. A chance for less experienced fighters can be that, particularly hip TGs extrapolate to the athletes' feet movement, which consequently comprise higher motion amplitudes. It further appears that 4 of the 6 fighters, who do not perform some kind of distance reduction between their feet are among the 10 most successful fighters of the study. Therefore, preliminary supporting leg (SL) stepping or in-bouncing movements might be ideal for athletes of different performance levels to detect and react on in a fight.

We conclude that one hand initiation actions serve biomechanical functions, such as securing balance and easing the distance reduction to the opponent. However, well trained fighters are able to react on even small-scaled Telegraphs (TGs). Therefore, athletes should try to avoid particularly relatively early TGs. Hip joint TGs might have thereby, the biggest disadvantage as they are happening early, and the resulting foot movement is easier to detect. Further research is needed to clarify, which of these movements are detected by athletes and which exact threshold lies between detection and oversight.

4.6 Limitations

This study aims to determine movements contributing to mechanical goals, which could be detected by an opponent. However, to gain a deeper understanding of these movements it would be necessary to analyse (a) the segmental impulse transfer, starting with the initiation action and contributing to the absolute power outcome, (b) the stability conditions during the kicking leg lift-off, and (c) the opponents anticipation and reaction.

Generally, larger samples would be beneficial to analyse differences of these movements between different performance levels.

Furthermore, the threshold between the angular range of the fighting movement and the determination of a Telegraph, which in the present study is reverse calculated from possible outcomes, should be defined by opponent reactions or statistical procedures with larger samples in future studies.

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6 Declaration of Interests Statement

The authors declare that there is no conflict of interest.

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Figures

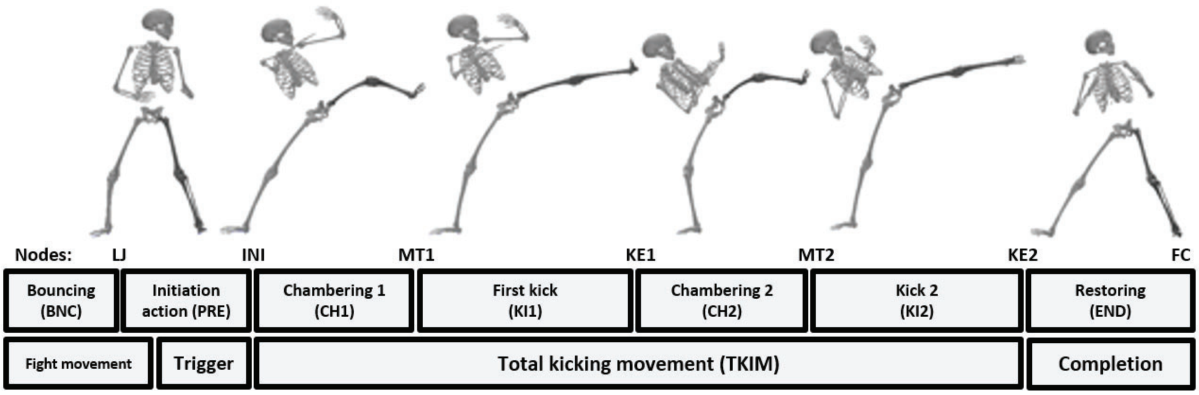


Figure 1: Double side kick technique description. The upper bar illustrates the phase definition by (Hölbling et al., 2017), while the lower bar provides a more general description of the kick combination.

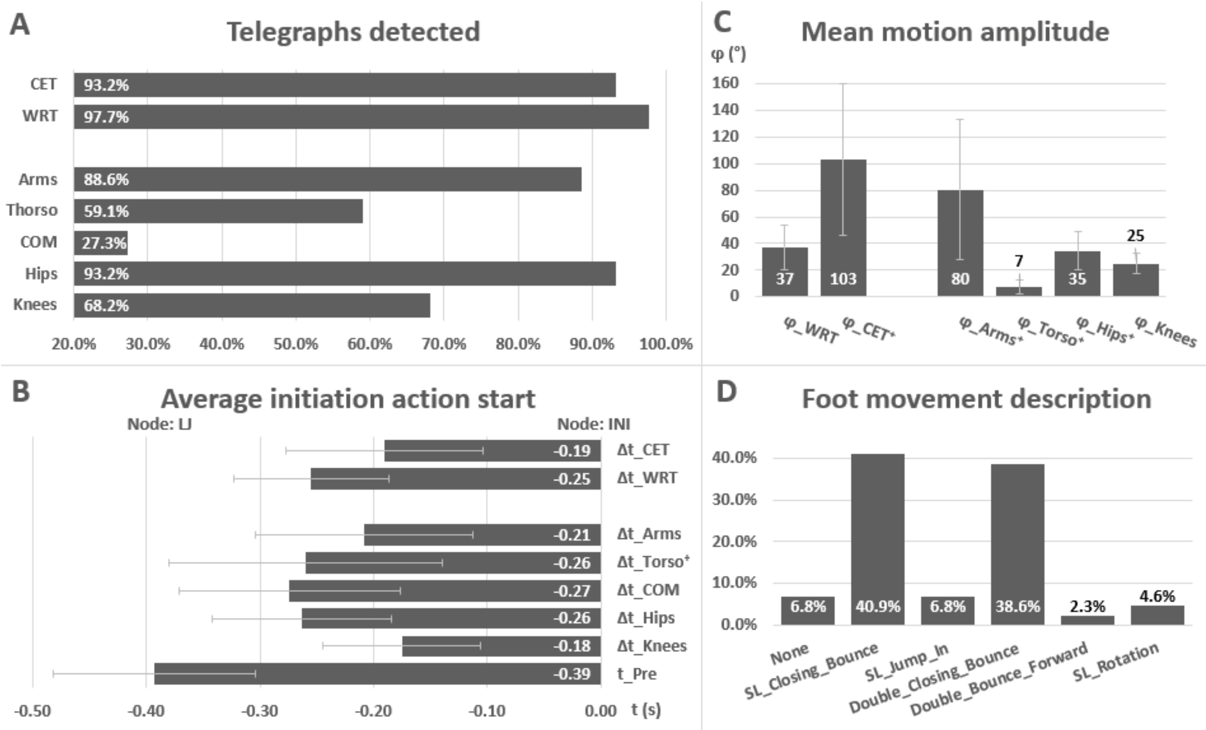


Figure 2: Descriptive statistics. A shows the percentage of fighters performing a specific category of Telegraphs. B shows average start of each initiation action category. C shows the mean motion amplitude of each initiation action category. D shows the percentage of fighters performing a specific foot movement based on qualitative analysis. +marks variables significantly differing from normal distribution and given as mean ± IQR.

Tables

Table 1: Inferential statistics of category and segment, motion start and amplitude differences.

A) Differences between WRT and CET in average motion start (t-test) and motion amplitudes (Wilcoxon test):

	Δt_categories	**φ_categories⁺**
p	<0.01*	<0.01*
T/Z⁺ Value	4.67	-5.69

B) Within-subject effects of average motion start (Friedman test) and motion amplitudes (Friedman test):

	Δt_segments⁺	**φ_segments⁺**
p	<0.01*	<0.01*
Friedman χ^2	17.94	17.94

C) Average ± SD (or Mean ± IQR⁺) and group differences of average initiation action start (Dunn-Bonferroni test):

Δt_Arms	**Δt_Torso⁺**	**Δt_COM**	**Δt_Hips**	**Δt_Knees**
0.21s	0.26s	0.27s	0.26s	0.18s
±0.10	±0.12	±0.10	±0.08	±0.07
p=0.03*			p<0.01*	
	p=0.02*		p<0.01*	
		p<0.01*		

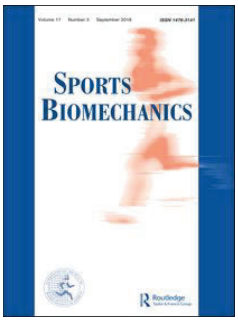
D) Average ± SD (or Mean ± IQR⁺) and group differences of motion amplitudes (Dunn-Bonferroni test):

φ_Arms⁺	**φ_Torso⁺**	**φ_Hips⁺**	**φ_Knees**
80.46°	7.38°	34.62°	24.73°
±52.70	±5.13	±14.61	±7.72
p<0.01*		p<0.01*	
	p<0.01*		
	p=0.02*		
	p<0.01*		

⁺marks variables significantly differing from normal distribution

12. Publication 3: A kinematic model for assessment of hip joint range-of-motion in fast sport movements using spreading angles.

Publication status: The following manuscript was accepted by the Sports Biomechanics Journal on 07/07/2020 (Hoelbling, Baca, & Dabnichki, 2020a).
Prof. Baca and Prof. Dabnichki contributed planning, proof-reading, and continuous assistance at the writing process to this paper. Literature search, test implementation and manuscript writing, was performed by Dominik Hoelbling.



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A kinematic model for assessment of hip joint range-of-motion in fast sport movements using spreading angles

Dominik Hölbling , Arnold Baca & Peter Dabnichki

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A kinematic model for assessment of hip joint range-of-motion in fast sport movements using spreading angles

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ABSTRACT
The work investigates the relationship between the leg spread and hip joint flexibility during kicking action of highly skilled martial artists. Vector-based spreading angles (VSAs), as a simplified way to assess kick execution patterns and movement ranges, are proposed. The first VSA measures the angle between the two femur vectors (i.e., upper leg spread), whereas the second describes the full-leg spread. The proposed measures were applied to 3D motion analysis performed on 33 participants at various skill levels who executed double side kicks and performed two static flexibility tests (hip joint flexion and abduction). Statistical analysis showed that the proposed parameters differentiate between skill levels. Both VSAs and VSA rate of change showed high Pearson correlation to the quality of execution (the average of 10 subjective kickboxing experts' evaluation scores) at critical instants of the kick execution , i.e., during the first leg elevation and kick (angles: $\rho > 0.8$; $p < 0.001$). In addition, they significantly correlated to maximum static hip abduction at any instant ($\rho = 0.37$–0.69; $p < 0.05$). The work established that both static and dynamic joint flexibility contribute to high-performance levels and could be used for initial selection and assessment of training effectiveness.

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KEYWORDS
Range of motion; flexibility; kinematic model; hip joint; martial arts

Introduction

Flexibility is defined as the capacity of the structures that make up the tissues such as muscles, tendons and connective tissues, lengthen through the available range of motion (ROM) minimising the joint passive torque, the muscle tendon-stiffness (passive) and the opposite force generated by the antagonist muscle contraction (active) (Alter, 2004; Moreira & Gonzaga, 2012). There are limited studies on the role of flexibility in sport. However, it seems that it is a pre-requisite for successful and injury-free kicking execution in Martial Arts (Probst et al., 2007). ROM declines considerably with age and periods of immobility (Roaas & Andersson, 1982), which further increases injury risk. However, when transferring kinetic energy and angular momentum, joints also need stability to prevent damage. Joint stability is normally achieved by antagonistic muscle co-contraction, where agonist and antagonist muscles activate simultaneously (Thibordee & Prasartwuth,

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2014; Moreira et al., 2016) to produce a high level of opposite forces around the joint (Moreira et al., 2019). Consequently, it impairs the optimal manifestation of flexibility or ROM during Martial Arts kicking (Moreira et al., 2018). Hence, to perform at a high level without incurring injuries, athletes need to achieve the right balance between joint stability and flexibility. Physiologically this means that strong and elastic muscles are required. The compromise between flexibility and stability in sport poses major challenges to athletes performing fast and powerful overreaching actions. Those include, but are not limited to ballet dancers, gymnasts and martial artists, as the specifics of their movements require extreme joint ranges. The resulting external and internal eccentric forces can cause serious damage if not neutralised by actively supporting and range limiting muscles, aptly called stabilisers and neutralisers, as well as the passive resistors in the form of tendons and ligaments (Chumanov et al., 2007). The martial artists' ability to absorb such forces is considered the main reason for them suffering less joint laxity-related injuries in comparison to ballet performers, despite performing similar or even bigger movement range (Shan, 2005).

Hip joint flexibility

Qualitative observations strongly indicate that hip joint flexibility is central to a successful performance in kicking based Martial Arts like karate and kickboxing. Specifically, maximum kick height is strongly associated with the hip joint flexibility. However, there is no clear association regarding sub-maximal joint movement range during technique execution. Particularly, there is an open question whether overshooting flexibility is required to successfully utilise submaximal movement range in martial arts kick performance.

Testing and analysis of range of motion

Tests for static hip flexibility like the toe-touch (Kippers & Parker, 1987) and side split tests (Amigó et al., 2010) are simple to perform but only provide a crude estimate of maximum values for loosely defined inter-limb angles in a static hold. However, movement range for fast sport movements like Martial Arts techniques is complex to analyse as synchronised multi-limb action is involved. The hip joint movement range during kick techniques involves a combination of flexion, abduction and rotation angles for both hip joints in addition to knee flexion (see Figure 1a). A global measure cannot be extracted by summing up the joint angles for the individual legs', as those angles are inherent to the local coordinate system fixed at the joint centre of rotation (see Figure 1a) and cannot be added directly in the 3D space. Furthermore, miniscule soft tissue movements are strongly affecting the accuracy of pelvis orientation and are, in turn, affecting all angular estimates. Therefore, an approach based on kinematic data reduction (Miller et al., 2010; Witte et al., 2010), could provide a global indicator that is less prone to bias and error. Such a measure would provide the means to assess and compare movement patterns across athletes.

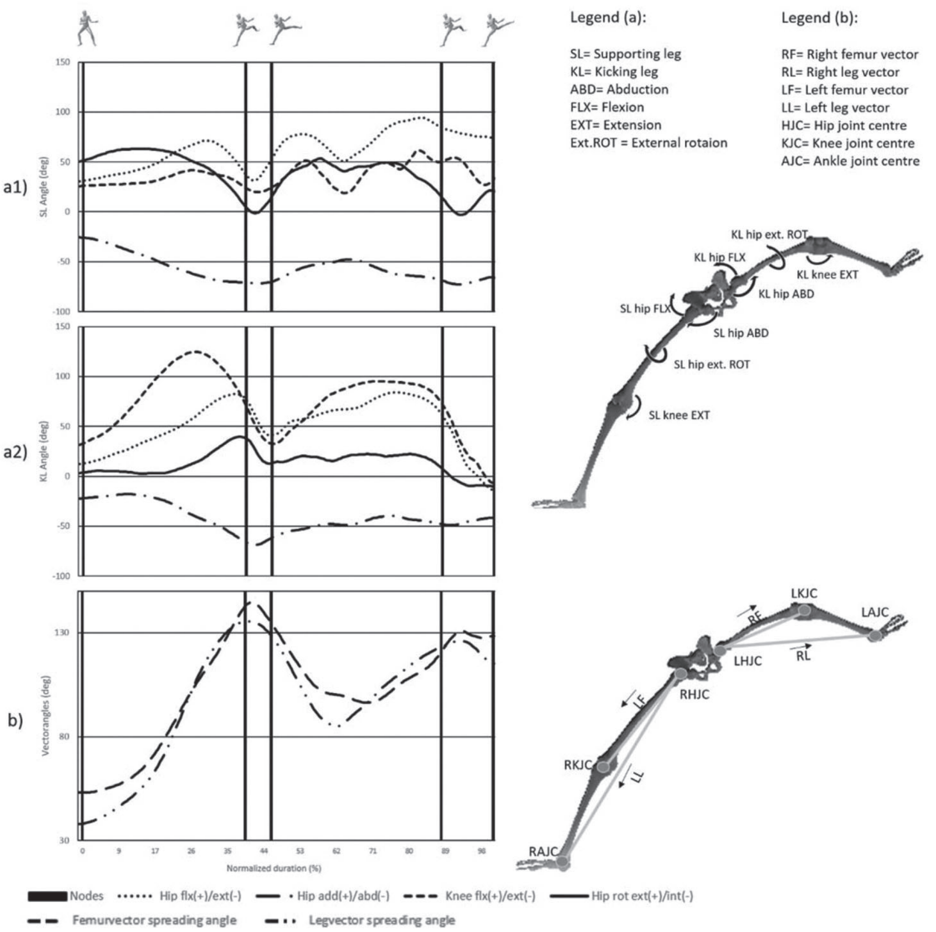

Figure 1. a1) Visualisation of relevant supporting leg angles for leg spreading assessment. a2) Exemplary visualisation of relevant supporting leg angles for leg spreading assessment. b) Proposed spreading angles for the femur and full leg vectors.

Martial arts kick combination (double side kick)

The double side kick (Hölbling et al., 2017) is characterised by two front leg sidekicks (see Figure 2). The action requires a high level of flexibility to avoid movement inhibition caused by antagonistic co-activation. It simultaneously comprises dynamic (leg elevation) and quasi-static (leg hold in the high position) elements, combined with high power release. It is therefore critical to be able to assess athletes' dynamic flexibility, which could potentially be the key factor behind their seemingly superior stability. Furthermore, it is essential to establish the role of flexibility in determining the skill level of an athlete by defining a set of simple and easy to measure variables that correspond to different skill levels. The complex inter-limb synchronisation occurring during a kicking action requires well-coordinated inter-joint action and is therefore reasonable to hypothesise the assessment of movement range is the more appropriate measure rather than the ROM of individual joints.

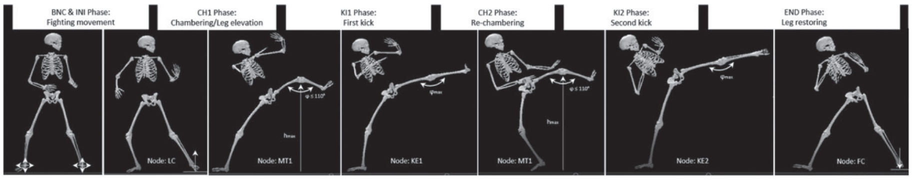

Figure 2. Movement phases and key nodes as defined by Hölbling et al. (2017)

Aims

The first aim of the study is to define a global measure that provides simple means for differentiation between skill levels in hip joint ROM during fast sport actions. Hence, our first hypothesis is H1: the defined set of angle parameters allows to objectively distinguish between the skill levels. The second aim was to establish the necessary levels of static flexibility and submaximal dynamic range of motion during Martial Arts kick technique execution for different performance levels. We formulated two further hypotheses, namely H2: There are significant correlations between the proposed VSA parameters at specific nodes (INI; MT1; KE1; MT2; KE2; FC) in the kinematic phase diagram with the technique success scores of the fighters and H3: the maximum static hip joint flexibility in flexion and abduction correlate at the same nodes.

Methods

Participants

The participating cohort consisted of 33 male volunteers from 7 countries and included 10 world and continental championship finalists; 9 world cup tournament winners; 6 national champions; 8 fighters with no noteworthy tournament success but at least 3 years of experience (appendix 2). The participants were divided into four groups based on their highest tournament achievement. Only tournament achievements in WAKO Pointfighting kickboxing (WAKO, 2019) were recognised for the group allocation. We note that 10 of the participants had also success in International Sport Karate Association sport karate (International Sport Karate Association, 2016). The study was approved by the University of Vienna ethics committee and all participants signed a general information form and a proof of consent.

Testing procedure, data collection and processing

All athletes signed the participant information and study consent form. Following a self-guided competition-like warm-up, 39 reflective markers were attached to specific landmarks on the participants' body defined in the plug-in-gait marker placement manual (Vicon® 2006) as shown in Appendix 3. The participant could perform some test movements. All participants performed series of three repetitions of the double side kick until fully satisfied with their performance. An execution was accepted for analysis when at least two kick motions were performed, and the second kick reached the punching bag with a thrust movement. The motion data were collected by an eight-camera Vicon® motion capturing system at 250 Hz sampling frequency. A high definition video camera simultaneously recorded the sagittal plane action for technique-ranking purposes. Marker trajectories were smoothed using cross-validated quintic splines (Woltring, 1986). The Vicon static and dynamic plug-in-gait models were used to obtain the required joint angles and centre of mass (COM) velocities. The functional skeleton calibration was applied for the joint centres of hip, knee and ankle (Vicon® 2006).

From the recordings, the trial with the fastest horizontal velocity of the COM was selected for further analysis. Each participant also performed two static flexibility tests immediately after the trials. Participants executed the toe-touch test for maximum hip flexion measurement (Kippers & Parker, 1987). The abduction was extracted from a sitting position, where participants abducted their extended legs as far as possible (side split adapted from Amigó et al. (2010)).

Kick performance observation and grouping

A group of 10 international coaches (6 national team coaches and 4 coaches with at least 3 national team fighters under their guidance) rated the quality of each execution on the perceived likelihood to score in a real tournament. They awarded a minimum of 1 (unlikely to score) up to 10 (certain score) points. The method was chosen to avoid bias due to the athlete's status and focus on the actual execution observed (a highly skilled hand fighter can achieve tournament success without being a high-level kicker).

Fighters were then ranked and divided into three groups according to their average performance points. The first group included the five top scoring fighters (>8 points). The second group of 14 fighters with an average score >5 and the third included the remaining 14 participants who scored less than 5 points. There was ≥0.3-point gap between the groups. The ranking was verified by comparing the athletes' scores to their respective tournament successes.

Variable definitions

A sequence of maximum stretches was used to calculate average flexion in the bending static test (Kippers & Parker, 1987) and combined abduction (Bozic et al., 2010) during the side split static test.

As a global indicator for movement range, vector spreading angles (VSA) between the legs during the technique execution were defined and calculated (see Figure 3). The spreading angles are defined as follows:

(1) φ_F describes the movement range accomplished by single-joint hip muscles (e.g., adductor brevis, magnus and longus), whereas
(2) φ_L additionally involves two-joint hip-knee muscles (e.g., biceps femoris and semitendinosus).

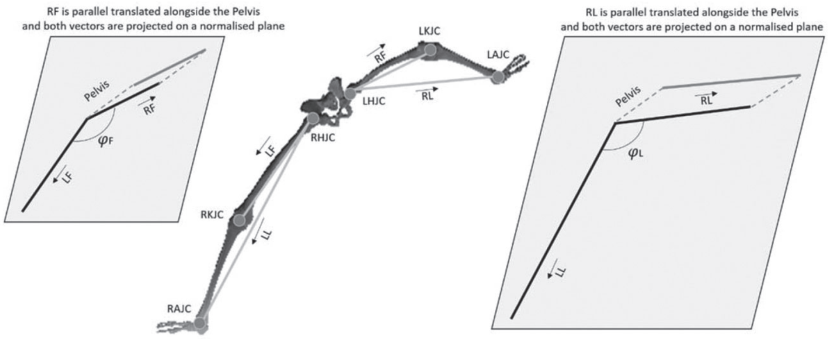

Figure 3. Schematic visualisation of femur (LF & RF) and leg (LL & RL) vectors between hip (LHJC & RHJC) and knee joint centres (LKJC & RKJC) and the vectors linking hip and ankle joint centres (LAJC & RAJC) for LL & RL. The spreading angles (φ_F & φ_L) are calculated for each vector pair (see formulae 1 &2). Top kickboxers are very flexible as they spread their legs faster and wider while using double kick.

Peak angles and the values obtained in specific key nodes were chosen for comparisons with the static flexibility tests and performance scores (see Figure 2 and phase & node definition).

$$\varphi_F = \cos^{-1}\left(\frac{\overrightarrow{LF}\,.\,\overrightarrow{RF}}{\left|\overrightarrow{LF}\right|\cdot\left|\overrightarrow{RF}\right|}\right) \tag{1}$$

The femur spreading angle $\varphi_{F,}$ using the left (LF) and right (RF) femur vector (see Figure 3) is calculated from the formula above and

$$\varphi_L = \cos^{-1}\left(\frac{\overrightarrow{LL}\,.\,\overrightarrow{RL}}{\left|\overrightarrow{LL}\right|\cdot\left|\overrightarrow{RL}\right|}\right) \tag{2}$$

the leg spreading angle $\varphi_{L,}$ using the left (LL) and right (RL) leg vector (see Figure 3) respectively.

Phase and node definition

The kicking phases (first chambering, CH1; first kick, KI1; second chambering, CH2; second kick, KI2; restoring phase, END) and kick leg motion-based nodes (last floor contact, LC; first measuring time MT1; first knee extension, KE1; second measuring time, MT2; second knee extension, KE2) of the locomotion were based on (Hölbling et al., 2017), as visualised in Figure 2 and further described in Appendix 1. However, in this study, the first two phases of the model were amalgamated into a single one called 'fighting stance' in the movement range analysis. Hölbling et al. (2017) recommended to use the time point the highest elevation of the kicking leg knee occurs and the knee extension is 110 degrees for MT1 and MT2.

In addition to the data simplification (see Figure 1), the proposed measure shows a small variance, as the angles are not affected by hip joint and pelvis rotations. Furthermore, it is not sensitive to errors in pelvis tilt estimates. In particular, the relatively large vectors allow to negate the noise affected the centre of rotation position (Dabnichki et al., 1997; Lauder et al., 2001).

Statistical analysis

The consistency of the coaches' scorings was analysed by performing an inter-rater reliability test (ICC 3,1).

The Shapiro Wilks test was used to analyse data normality. Variables that differed significantly from a normal distribution are presented as median ± inter-quartile range (marked *), all others are given as mean ± standard deviation. Correlations were tested using Pearson's $\boldsymbol{\rho}$ correlation coefficient for normally distributed variables or Spearman's $\mathbf{r_S}$ rank correlation. Correlations between (a) mean technique success scores with the static flexibility tests and all VSA related variables and (b) the static flexibility tests with all VSA related variables were obtained.

Results

The consistency of the scorings between the 10 international coaches was observed using the interclass correlation coefficient test ICC (3,1), which showed a high correlation of 0.937 ($p < 0.001$). To relate the mean scorings for every fighter into real life (competition) perspective a Spearman's r_S between the average kick performance scores and the competition categories (1–4; see sample) was performed and also showed a high correlation of 0.745 at $p < 0.001$.

The mode of parameter reduction, as illustrated in Figure 1 and further specified in Figure 3, describes the VSA sequence (Figure 1b) of a representative participant's double side kick when compared to the standard set of hip joint angles (flexion, abduction and rotation) for both legs Figure 1(a1, a2). These VSA values are taken at fighting stance and all kick related nodes (INI; MT1; KE1; MT2; KE2; FC). All results are shown in Figure 4, in particular static flexibility tests (top left corner), the average peak values (bottom left corner), the average values at all nodes (bottom and top middle) and the relative, average angular velocities (bottom and top right), for both VSA. The correlation between (a) the mean technique performance scores and all flexibility and VSA-related variables and (b) the correlation between the static flexibility tests and VSA variables are shown in Table 1. A significant correlation was obtained between the mean scores (representing the technique success) and VSA at the nodes (Femur: INI, MT1, KE1, MT2, MAX; Leg: MT1, KE1, MT2, MAX). The scores also correlate with VSA angular velocity during most phases (Femur: CH1, CH2; Leg: CH1, KI1, CH2) and maximum static hip abduction with VSA at all nodes.

Table 1. Inferential statistics: a) Correlations between mean scores and VSAs, angular velocities and static flexibility tests. Pearson's ρ obtained for normally distributed variables; Spearman's r_s for variables differing significantly from the normal distribution. b) Correlations between static flexibility tests and dynamic VSAs and angular velocities.

	ϕF_INI	ϕF_MT1	ϕF_KE1	ϕF_MT2†	ϕF_KE2†	ϕF_Max	ϕL_INI	ϕL_MT1	ϕL_KE1	ϕL_MT2	ϕL_KE2	ϕL_Max
Mean scores ρ/rS	0.41*	0.84**	0.83**	0.41*	0.21	0.46**	0.25	0.84**	0.84**	0.48**	0.27	0.56**
Sig. (2-tailed)	0.018	<0.001	<0.001	0.017	0.231	0.006	0.156	<0.001	<0.001	0.004	0.137	0.001

	ωF_CH1	ωF_KI1	ωF_CH2	ωF_KI2	ωL_CH1	ωL_KI1	ωL_CH2	ωL_KI2	static_flx	Static_abd
Mean scores ρ/rS	0.66**	0.31	−0.73**	−0.07	0.78**	0.46**	−0.75**	−0.01	0.33	0.70**
Sig. (2-tailed)	<0.001	0.079	<0.001	0.707	<0.001	0.007	<0.001	0.958	0.061	<0.001

	F_INI	F_MT1	F_KE1	F_MT2†	F_KE2†	F_Max	L_INI	L_MT1	L_KE1	L_MT2	L_KE2	L_Max
Static_flx ρ/rS	0.26	0.21	0.24	−0.12	0.06	0.07	0.14	0.19	0.24	0.14	0.01	0.09
Sig. (2-tailed)	0.150	0.241	0.170	0.496	0.723	0.687	0.445	0.287	0.188	0.440	0.946	0.613
Static_abd ρ/rS	0.53**	0.66**	0.69**	0.49**	0.37*	0.56**	0.44**	0.65**	0.67**	0.44*	0.41*	0.56**
Sig. (2-tailed)	0.001	<0.001	<0.001	0.004	0.034	0.001	0.010	<0.001	<0.001	0.011	0.016	0.001

	ωF_CH1	ωF_KI1	ωF_CH2	ωF_KI2	ωL_CH1	ωL_KI1	ωL_CH2	ωL_KI2	ωF_CH2	ωL_KI1	ωL_CH2
Static_flx ρ/rS	0.10	0.15	−0.21	0.22	0.18	0.15	−0.09	−0.18	−0.21	0.14	−0.09
Sig. (2-tailed)	0.593	0.396	0.248	0.226	0.314	0.422	0.611	0.318	0.248	0.422	0.611
Static_abd ρ/rS	0.39*	0.37*	0.51**	0.11	0.52**	0.36*	−0.53**	0.03	−0.51**	0.36*	−0.53**
Sig. (2-tailed)	0.024	0.034	0.002	0.555	0.002	0.038	0.001	0.855	0.002	0.038	0.001

* Correlation is significant at 0.05 level (2-tailed)
** Correlation is significant at 0.01 level (2-tailed)
† Variable differs significantly from normal distribution

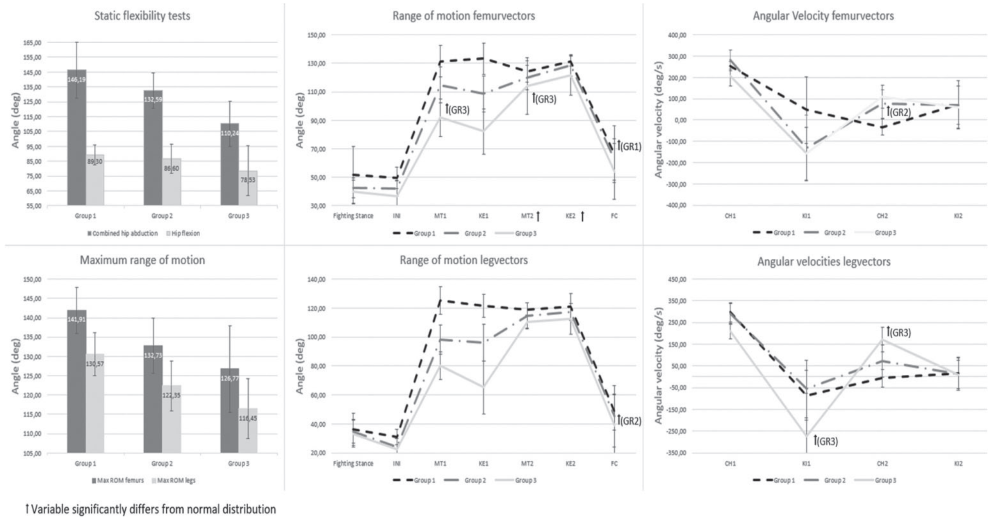

Figure 4. Descriptive statistics of the static flexibility tests (top left corner), the average maximum values (bottom left corner), the average values for all nodes (bottom and top middle) and relative average angular velocities (bottom and top right) for both VSA. Median and interquartile range is given for variables differing significantly from normal distribution, all others are shown as median and SD.

Discussion and implications

The independent performance indicator based on experts' assessment is valid as both assessment consistency and correlation with tournament success show the highest significance and large effect size (Hölbling et al. (2017)). This finding justifies a statement that (a) coaches can assess the quality of a kicking technique and (b) majority of successful tournament fighters perform superior kicking techniques.

Vector-based spreading angles (VSA)

Generally, it can be stated that the proposed measurements can distinguish between fighters at different skill levels, as 13 out of 20 VSA variables show a significant correlation to the technique success mean scores (Table 1a). High correlations ($\rho > 0.8$ in MT1 and KE1) between the technique success scores and the VSA (shown in Table 1a) in phases with greater differences between the groups (see Figure 4) further strengthens this statement. Therefore, H1 is accepted.

VSA and technique success

Fighters differed most profoundly in the first leg elevation and kick for both VSAs, where movement patterns are not constrained by targeting Figure 4. This is supported by the significant correlation between the mean scores and the VSAs in these sections (Table 1a; e.g., ϕ_L_MT1: $\rho = 0.84$; $p < 0.01$). Although all groups have the same normalised kick height (at MT2 and KE2), the higher skill groups show larger angles, which still shows a significant correlation at MT2 for both VSAs. This could be explained by the higher hip abduction of the kicking leg, which enables athletes to perform the technique with lower pelvis tilt which in turn leads to higher movement range at the supporting leg's hip joint, especially in flexion (see Figure 5). Therefore, we conclude that the VSA method is well suited to identify differences in movement patterns and distinguish between skill levels. Therefore, H2 is also accepted.

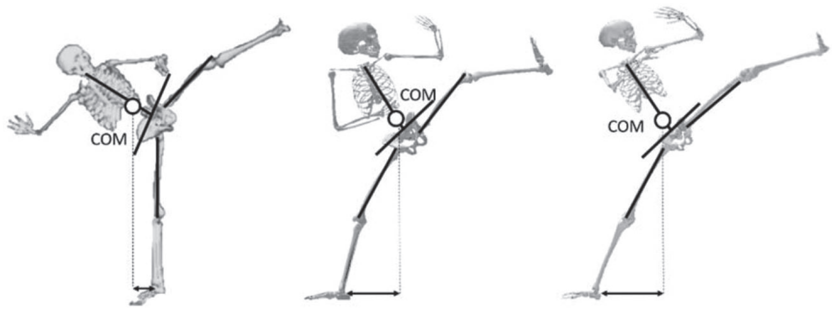

Figure 5. Exemplary comparison of body positions at target contact between a group 2 fighter (left) and two group 1 fighters (with different styles). Graphical estimation of thorax, pelvis and femur axes as well as COM are schematically drafted.

Based on the correlation between the angular velocities and mean scores (ωF_CH1: $\rho = 0.66$; $p < 0.01$; ωL_CH1: $\rho = 0.78$; $p < 0.01$), the change in VSA angles is fastest at CH1, especially for the better fighters and declines to near zero afterwards Figure 4. This means that successful fighters elevate the kicking leg very fast in the first chambering phase then hold the kicking leg at nearly constant height afterwards, whereas the supporting leg moves to close the distance.

Table 1b illustrates that most of the differences in VSA between the skill groups are due to hip joint abduction and not flexion, further supported by and illustrated in Figure 5.

VSA and static hip joint flexibility

Static hip joint flexibility for the elite athletes in this study flexion is 89.30° ± 6.65 for flexion and in combined abduction 146.19° ± 18.48. Furthermore, there is a significant correlation between the abduction and the mean scores ($\rho = 0.7$; $p < 0.01$) indicating that the better fighters have higher static flexibility (Figure 4; Table 1a). However, differences in flexion between the groups are smaller and do not show statistically significant correlation with the technique success. It is further noted that differences in static flexibility between groups could be partially related to the age difference (Appendix 2).

There are also significant correlations between static hip joint abduction and 21 out of 23 VSA related variables but no correlations between static hip joint flexion and VSA variables. Therefore, hypothesis 3 can only be accepted for the combined hip joint abduction and should be rejected for flexion.

The proposed set of angular variables allows us to effectively measure and improve the kicking performance of the athletes.

Limitations

In the present study, groups we separated solely on performance characteristics, particularly the first group of five athletes with outstanding performance. The remaining sample was divided into 2 equal groups of 14 participants. However, the introduction of objectively measured parameters is advisable and should be implemented in the future work.

Further assessment of muscle elasticity and strength should determine how these parameters are affected by the athlete's strength, stability and flexibility.

Practical implications

The developed method for measuring static flexibility and dynamic movement range is methodologically simple but can be efficiently used for inter-athlete (comparison of different athletes) and intra-athlete (comparison of different performances of the same athlete) movement pattern analysis. Additionally, it could be used in research about injury probability related to the range of motion.

Our results justify the development of training routines and devices allowing appropriate amalgamation of balance, stability and high flexibility.

Conclusion

The results demonstrated that both VSAs are related to subjective (technical quality) and objective (ranking) performance success in kickboxing. We have found that both static and dynamic joint flexibility play important roles in achieving high-performance levels and they could also be used for initial selection purposes.

Acknowledgments

We would like to thank our laboratory assistant, as well as all fighters who participated in this study.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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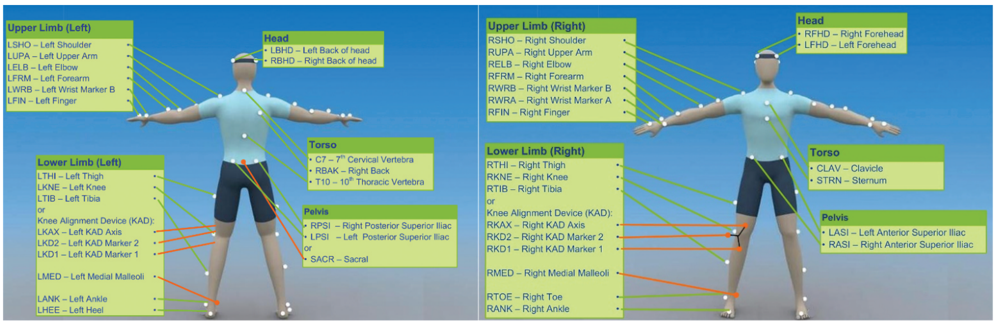
Appendix 1: Abbreviations

Abbreviation	Description
ROM	Range of motion
VSA	Vector based spreading angle
ϕ_F	VSA between both femurs (defined between hip and knee joint centres)
ϕ_L	VSA between both femurs (defined between hip and ankle joint centres)
Phases:	
CH1	First chambering phase between the nodes LC and MT1
KI1	First kicking phase between the nodes MT1 and KE1
CH2	Re-chambering phase between the nodes KE1 and MT2
KI2	Second kicking phase between the nodes MT2 and KE2
END	Leg restoring phase between the nodes KE2 and FC
Nodes:	
LC	Last floor contact of the kicking legs' foot before the kick
MT1	Measuring time1: Frame with highest knee position at a KL knee angle below 110° between LC and KE1
KE1	First kick: Frame with maximum knee extension of the KL before re-chambering
MT2	Measuring time2: Frame with highest knee position at a KL knee angle below 110° between KE1 and KE2
KE2	Second kick: Frame with maximum knee extension of the KL between MT2 and FC
FC	First floor contact of the KL foot after the kicks

Appendix 2: Description of participant groups

Group	n	Performance (points)	Age (years)	Body weight (kg)	Body height (m)
Group 1	5	8.24 ±0.13	19.60 ±5.32	77.10 ±5.50	1.86 ±0.04
Group 2	14	6.46 ±0.85	28.21 ±6.60	79.54 ±11.67	1.81 ±0.10
Group 3	14	4.03 ±0.56	30.79 ±8.46	79.36 ±10.29	1.85 ±0.09

Appendix 3: Vicon plug-in-gait marker model (Taylor et al., 2006)



13. Publication 4: The Flexibility Trainer: Feasibility Analysis, Prototype- and Test Station development for a Sports Device for Hip-Joint Flexibility and Strength Enhancement

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Prof. Baca and Prof. Dabnichki contributed planning, proof-reading, and continuous assistance at the writing process to this paper. Description of components, hip moment calculations and Finite Elements Analysis was added by Prof. Grafinger. Literature search, hip moment equations and manuscript writing (Introduction, parts of Results and Discussion and Conclusions), was performed by Dominik Hoelbling.

The Flexibility Trainer: Feasibility Analysis, Prototype- and Test Station Development for a Sports Device for Hip-joint Flexibility and Strength Enhancement

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Keywords: Flexibility, Strength, Sports Engineering, Hip Joint, Martial Arts, Dancing, Gymnastics.

Abstract: Martial Arts, dancing, and gymnastics are among the sports that depend on outstanding hip-joint flexibility and strength to successfully perform high level techniques. Latest research suggests that flexibility and antagonistic strength are strongly related and require agonistic strength training. Therefore, the aim of the study was to develop a model prototype of a device that utilises flexibility-enhancement reflexes and provides appropriate means for strength training and delivers hip joint range-of-motion (ROM) increase. The device provisionally called Flexibility Trainer (FT) is equipped with sensors that measures and estimate the athletes' hip joint moments during training. The FT aims to utilise the athletes body weight while performing controlled leg spreads. Its main components are a rail system with 2 slides and foot mounts (tiltable and turnable), a hydraulic braking system for force independent constant velocity slide (nearly isokinetic), a force sensor and a holding device. It is hypothesised that the leg-spread movement activates the reciprocal-inhibition reflex and increases antagonistic strength, whereas the leg-closing movement activates the autogenic-inhibition reflex and leads to serial hypertrophy. A model for hip-joint moment calculation based on force sensor and motion capturing data is proposed.

1 INTRODUCTION

Hip-joint flexibility (HJF) and strength are essential pre-requisites for most sports, but particularly Martial Arts, dancing and gymnastics that are highly dependent on it (Hölbling, Preuschl, Hassmann, & Baca, 2017; Shan, 2005; Weber, Bedi, Tibor, Zaltz, & Larson, 2015).

Training this ability can be challenging, as the improvement of the range-of-motion (ROM) involves physiological and neuronal adaptations (Alter, 2004; Moreira & Gonzaga, 2012) and it decreases with age and periods of immobility (Roaas & Andersson, 1982). However, recent research suggests different physiological and neuronal methodical approaches result in measurable short- and long-term adaptions of active and passive hip-joint flexibility.

1.1 Methodical Approaches for Short-term Adaptions of ROM

Most short-term approaches are based on neuronal adaptions, such as decreased residual muscle tone and increased stress tolerance (Sharman, Cresswell, & Riek, 2006). Current publications have outlined the benefits of reciprocal and autogenic inhibition activation (Rowlands, Marginson, & Lee, 2003).

1.1.1 Reciprocal Inhibition

Reciprocal inhibition is "a process that inhibits the stretch reflex in antagonistic pairs of muscles. When

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one muscle contracts it sends inhibitory nerve impulses to its opposing muscle causing it to relax" (Kent, 2006, p. 458). Therefore, the reflex can be used inversely to increase the flexibility in one muscle, by contracting its antagonist.

1.1.2 Autogenic Inhibition

Autogenic inhibition (or inverse myotatic reflex) describes a "reflex inhibition of a motor unit in response to excessive tension in the muscle fibres it supplies" (Kent, 2006, p. 62). The reflex results in increased ROM after contraction of the limiting muscles.

1.1.3 CRAC- PNF Training

Proprioceptive neuromuscular facilitation (PNF) training describes "an effective stretching technique for increasing the joint's range of motion. All PNF procedures require a partner and involve a pattern of alternating muscles' contraction and relaxation while stretched. In this way the Golgi tendon organs are stimulated (Kent, 2006, p. 441). A particular promising variant called Contract-relax-agonist-contract (CRAC) combines a contraction of the targeted (stretching) muscle (TM), followed by relaxation and contraction of the opposing muscle (OM) to reach a wider position culminating in additional passive stretch (Sharman et al., 2006). This method is believed to activate both, reciprocal and autogenic inhibition, which results in a significantly higher ROM increase, compared to traditional flexibility training methods. Sharman et al. (2006). report a gain of 3-9° in joint angle by this method, which would theoretically result in 6-18° for full leg spreading.

1.2 Methodical Approaches for Long-term Adaptions of ROM

Long-term enhancements in flexibility are normally accompanied by physiological adaptions. Thereby, active ROM is strongly dependent on OM (agonist of the spreading movement) strength, whereas passive flexibility is primarily related to the stretching muscle's length and elasticity. Recent research reported that full-ROM strength training (if performed in both opposing movement directions) leads to both increase of OM strength and serial hypertrophy (particularly eccentric motions) of the TM (Csapo, Alegre, & Baron, 2011; Franchi et al., 2014).

1.2.1 Agonistic Strength

The agonistic muscle (OM) strength constitutes a key factor to significantly enhance active flexibility, especially in fast sports movements opposing the gravitational pull. Increase in maximum strength can be achieved by intramuscular strength (IC) or (parallel) hypertrophy training (HT). This requires 1 to 3 repetitions at 90-100% of one repetition maximum (1rpm) resistance for IC or 8-12 with 60-80% of 1rpm for HT, varying between authors.

1.2.2 Serial Hypertrophy of TM

Recent research states that full-ROM strength training, particulalry (but not solely) in eccentric motion leads to increased muscle length, due to additional serial muscle fibre sarcomere production (Csapo et al., 2011; Franchi et al., 2014).

1.3 Isokinetic Training

To enable a sport device to allow for different number of repetitions and percentages of 1 rpm and to simultaneously decrease the injury propability, an isokinetic mode is believed to be advantageous. Isokinetics in general describes "exercise with an accommodating resistance and a fixed speed" (Brown, 2000, p. 6).

1.4 Device Development

The aim of the study is (a) to design a device which combines static and dynamic CRAC-PNF with full-ROM strength training in an isokinetic training mode for an increase of hip joint flexibility in side (abduction/ adduction) and front split (flexion/ extension) direction, (b) to investigate its' feasibility (c) to manufacture a simplified prototype and (d) to propose an appropriate participant specific test setup.

2 MATERIALS AND METHODS

The design process was structured in four main phases *product planning*, *conception*, *product design* and *detailing for production* according to Pahl and Beitz (2013) and VDI2221 (2019). The first 2 phases are considered as pre-analysis phases and can therefore be found in the methods section, whereas later include detailed calculations, which can be found in the results and discussion section.

Planning Phase: A requirement list was developed to address customers' needs as outlined in Hölbling (2016) and illustrated in Table 1.

Table 1: Requirement list. The list covers customer needs and patent specification from Hölbling (2016). Table column 2 distinguishes between fixed requirements (F) and wanted requests (W).

Function	**F/W**	**Description**
Sliding system	F	Linear movement direction
Sliding system	F	Coupled motion for symmetric exercises
Sliding system	W	Foldable for easy transportation
Feet fixations	F	Fixation of feet on sliders rotatable around 360°
Feet fixations	F	Foot fixations must be tiltable >40° to avoid ankle injuries
Damping system	F	Damper to slow down foot rotation in the foot ankle joint
Brake system	F	Movement with adjustable velocity from 0,1 m/s to 0,3 m/s, at design load of maximum expected load.
Frame	W	Minimized weight for easy transportation
Handle	F	Adjustable in height
Force Sensor	W	Measure the combined leg spreading and closing force, withstanding maximum loads.

Conception Phase: To achieve the main functions, the product was segmented into functional modules: *rail system*, *sliders*, *braking system*, *holding device* and *force sensors*.

The *design phase* includes detailed descriptions of the main device components of a first market-ready version, including stress analysis, due to the external loads during usage. Therefore, this section covers *aim a-b*.

In the *detailing phase* some changes of the device design are proposed, to address *aim c*.

A setup for device testing and analysis of general and sport specific flexibility is proposed as stated in aim d).

3 RESULTS AND DISCUSSION

3.1 General Components

The outlined design consists of two sliding mechanisms (1), running on U-Profiles (2) with rotating foot straps (3), shown in Figure 1. The foot straps can be set by locking pin at every 90°. The sliders are connected with a circulating steel cable (4) guide rollers are located at the outer end (5) of the U-Profiles to ensure symmetric motion. The damper unit of the braking system (6) is placed inside the U-Profile. The trainer can be folded at the connection plate (7) for easy transportation. The handles (8) are height adjustable by lock pins (9) and are mounted in injection moulded foldable plates (10).

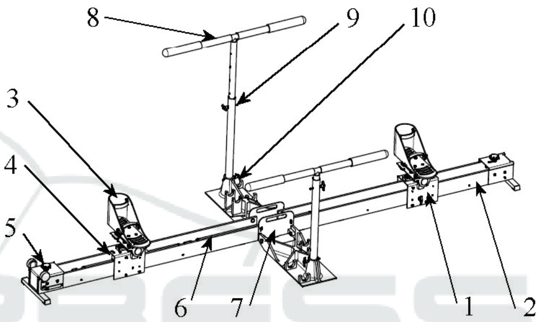

Figure 1: Design of Flexibility trainer.

3.2 Calculations of External Loads

The expected user generated maximum loads are calculated using maximum hip moment and the user's weight (see Figure 2).

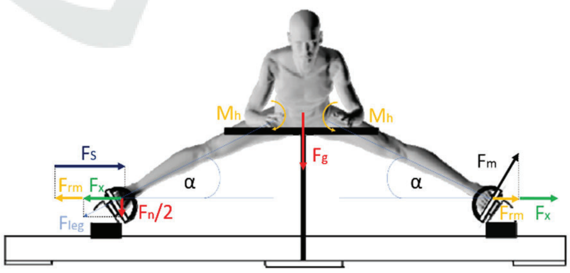

Figure 2: Illustration of the force calculation method in abduction [4].

[4] Legend:
F_g = Gravitational force
F_n = Normal component of gravitational force
F_x = Horizontal component of gravitational force
F_{rm} = Horizontal component of muscular force
F_S = Spreading force
M_h = Cumulated moment of hip joint
g = Gravitational acceleration
α = angle leg axis to floor
l_{leg} = leg length
h_{eff} = effective component of leg length

For the calculation of F_{rm}, the possible M_h from an Isokinetic test is approximately linearized (based on the isokinetic hip abduction and adduction test of a highly skilled Martial Artist, shown in Appendix A and divided by effective height.

$$F_{rm} = \frac{M_h}{h_{eff}} = \frac{150\,Nm - 1.35\,\frac{Nm}{°} * (90° - \alpha)}{l_{leg} * \sin(\alpha)} \quad (1)$$

The component F_x of bodyweight F_g is

$$F_x = \frac{F_g}{2 * \tan(\propto)} \quad (2)$$

The resulting maximal force on the slider is the sum of F_{rm} and F_x equal to approx. 2200 N at the minimal possible α of 15°. Leg length is assumed 1 m and the body weight up to 110 kg (see Figure 3).

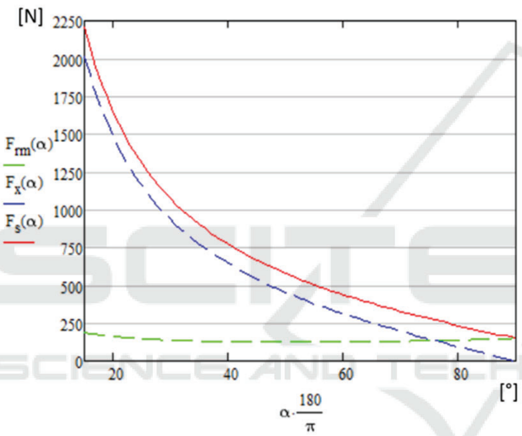

Figure 3: Horizontal forces on slider depending on α.

This is also the assumed load for the braking system and the other slider components. The selected damper should work for speed up to 0.3 m/s at this load.
The force sensors should have a range from 100 N to 5000 N in pulling and pushing directions.

3.3 Components and Specific Loads

3.3.1 Rail System

The main part of the rail systems are the U-Profiles 100x80x10 mm. For weight reduction purpose the chosen material is *Polyamid*. Maximal stress and deformation is obtained via *FEA* (*Finite Elements Analysis;* (Klein, 2012)*)*. Maximum stress level of 25 MPa is located around the mounting holes as expected and is well below the critical stress level (Figure 4). The detailed model description is available in Stummer (2016)

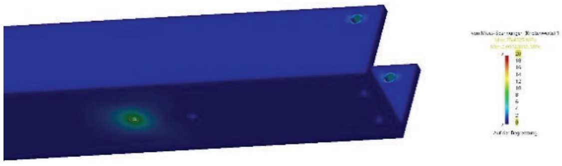

Figure 4: *Von Mises* stress on polyamid U-Profile (Stummer, 2016).

Inside the rail track two adjustable hydraulic brake cylinders *HB-40-500* and *HB-40-600* (6) from supplier *ACE* (Figure 5) are placed in series. The maximum allowed force is 4000 N for the longer 600 mm cylinder.

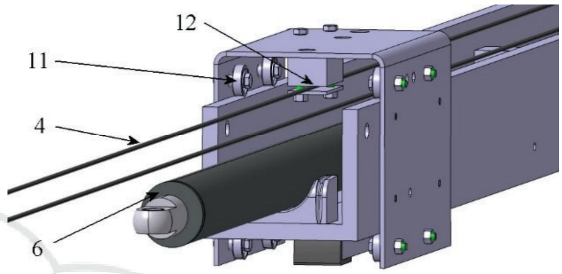

Figure 5: Rail and slider system of one side.

The sliders are running on the U-Profile with *SKF 635 ball bearings* (11) to minimize the friction. Both sliders are clamped to the steel cable (4) by sheet metal (12) and *M5 screws*. For cable turn at the end of the U-Profile *guide pulleys 10/3* (13) from *Ingo Quirnbach Industrieservice* are applied (Figure 6). The two upstanding *rollers 20K JGV 050-2* (14) from *Dematech* are for transportation issues.

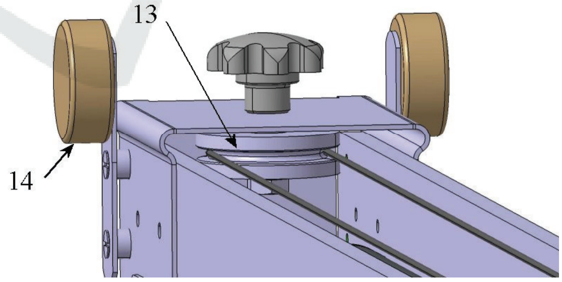

Figure 6: Rollers at the outer end of the U-Profile.

3.3.2 Sliders

The main frame of the slider is profiled from a metal sheet of 3 mm thickness and connected to the braking system by a detachable lock pin (15) as shown in Figure 7. This enables dismantling for folding and transportation.

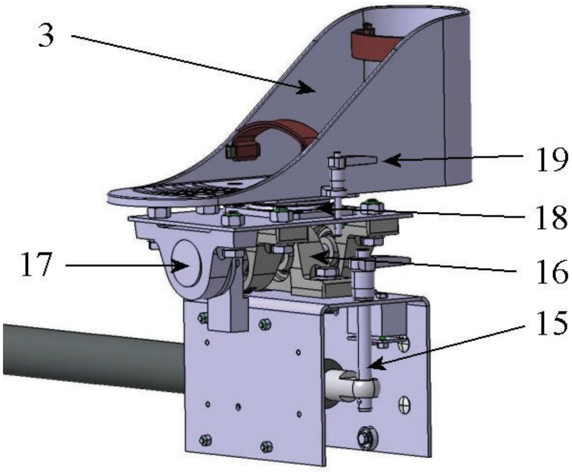

Figure 7: Slider with ankle tilt system and foot mount.

The ankle tilt mechanism, consisting of roller bearings with housing *SY 12 TF* from *SKF* (16) and *rotational damper WRD-H-3015-C* from *Weforma* (17), is mounted on the slider frame. The torque of the selected damper is adjustable from 2 to 14 Nm and should reduce unintended ankle wobble.

A turntable (18) is placed between the foot mount and the ankle tilt mechanism to allow the foot mount rotation of 360° for spread training lateral and longitudinal. It can be fixed every 90° by the lock pin (19).

The foot mount (3) is manufactured by *FDM (Fused Deposition Modelling)* for the prototype. For serial production it will be injection moulded.

3.3.3 Holding Device

The choice of material for the tubes (8), of this essential safety feature as shown in Figure 8, is *CFRP* (carbon fibre reinforced plastic). Pre-ordered tubes can be glued together with aluminium T-piece (20) to form the handlebar. For ergonomic reasons, the handlebar is height adjustable and fixed by a lock pin (9).

The connection plate (10) is an injection moulded part. The maximum stress is calculated at a horizontal force of 300 N on the handlebar that leads to a bending moment of 270 Nm at the tube mounting dome. The *FEM* results show a maximum stress of 42 MPa at a single node (see Figure 9 and Stummer (2016) for more details).

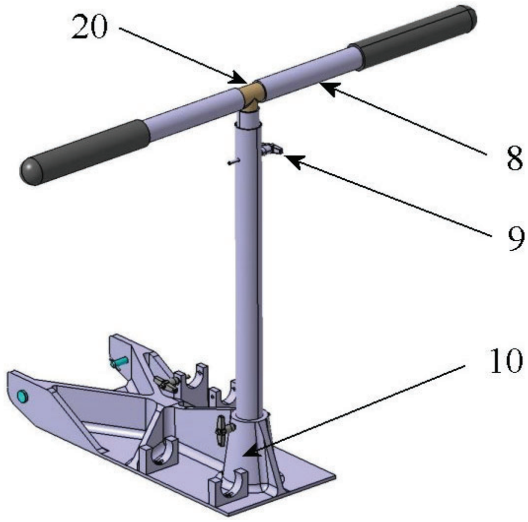

Figure 8: Handlebar of *CFRP tubes*.

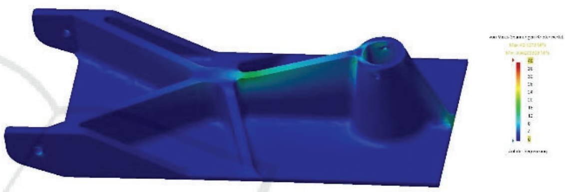

Figure 9: *Von Mises* stress on connection plate (Stummer, 2016).

The maximum stress in the ribs is less than 20 MPa i.e. safely below critical stress.

3.3.4 Force Sensor

As stated in section 0, the expected maximum force at the sensor is about 2200N per leg. Therefore, the sensor should have a measuring range from 100N-5000N. A *U9c force sensor* for forces up to 20kN has been identified.

3.4 Changes for the Prototype

Due to manufacturing reasons some parts of the design needed to be changed from the planned serial manufacturing to prototyping (see Figure 10):

- Due to high costs, the injection moulded mounting plates were changed to aluminium plates.
- The minimum length of Polyamid U-Profile was changed to aluminium profile.

- As a consequence of the rail profile change the sliders are now running on linear guide inside the profile instead of the roller bearings outside.
- The foot mount changed from a 3D printed part to mini skates available on the market.
- The holding devices are made of steel.

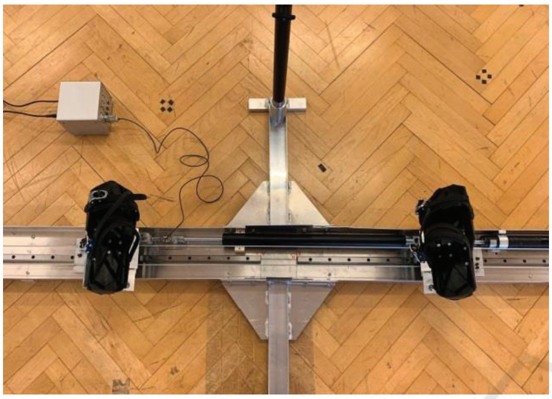

Figure 10: Manufactured prototype.

3.5 Proposed Test Setup

In order to comprehensively test the device and its short-term effect on athletes, a testing setup utilizing a *Vicon® motion capturing system* and a force sensor within the device for measuring the force alongside the rail, is proposed. The setup is specifically designed to provide a detailed estimation of the hip joint moments, to evaluate the athletes' physical strain during exercising in order to make propose future training adaptations. In addition, the setup includes a stage for practical measurements, such as static flexibility tests and sport specific movements, as well as a stage for device training.

3.5.1 System Setup

As stated above, the setup comprises both, one sport-specific (e.g. Martial Arts) and one device-specific movement analysis volume. The combined volume is surrounded by 12 high-resolution infrared cameras, specifically aimed to capture all markers, which are attached to the athlete during the exercises, see Figure 11.

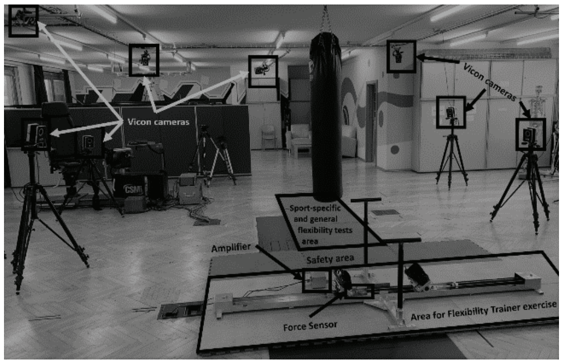

Figure 11: Proposed test setup for sport-specific and general flexibility tests.

3.5.2 Hip-joint Moment Calculation

To calculate the hip joint moment with inclusion of the external forces of the flexibility trainer, a kinematic model of the hip joint centre, based on a marker model and anthropometric data is required. The Vicon® plug-in-gait model is applied (Vicon®, 2016). Hip joint angles can be obtained using the *static and dynamic* plug-in-gait modelling function. Centres of rotation are calculated by the *functional skeleton calibration*.

Based on Figure 2, the cumulative hip moment (for leg spreading) can be estimated by following inverse calculation retrieved from the linear sensor force and reduced by the gravity component[5]:

$$M_h = \frac{F_S - {}^1/_2 \times F_g \times \cos(\propto)}{\cos(90-\propto)} \times l_{leg} \tag{3}$$

The cumulated hip-joint moment M_h can then be divided into the 3 movement direction components[6] (M_x, M_y, M_z) by splitting it in relation to the calculated components from Vicon® (M_{Vx}, M_{Vy}, M_{Vz}), as the kinematic parameters, such as movement directions are the same with and without resistance.

$$M_x = \frac{M_h}{M_{Vx}+M_{Vy}+M_{Vz}} \times M_{Vx} \tag{4}$$

$$M_y = \frac{M_h}{M_{Vx}+M_{Vy}+M_{Vz}} \times M_{Vy} \tag{5}$$

$$M_z = \frac{M_h}{M_{Vx}+M_{Vy}+M_{Vz}} \times M_{Vz} \tag{6}$$

[5] For Legend, see Figure 2
[6] Legend:
M_x = Hip flexion moment
M_y = Hip abduction moment
M_z = Hip rotation moment
M_{Vx} = Vicon® calculated hip flexion moment
M_{Vy} = Vicon® calculated hip abduction moment
M_{Vz} = Vicon® calculated hip rotation moment

3.6 Summary of Outcomes

The proposed final construction fulfils additional framework conditions, such as weight and design specifications, which will be necessary for a commercially viable product, but are too expensive for a prototype. Therefore, the design was optimized in order to provide more safety and stability for significantly lower costs. The testing setup is opted to provide analysis possibilities for sport-specific and general flexibility tests, as well as for the device training analysis. Furthermore, to comprehensively analyse the physical strain during the training, a mathematical model for joint moment analysis was used, based on the Vicon® model and the force sensor data.

3.7 Limitations

The calculation model does currently solely comprise the leg spreading motion because at the leg closing motion the participant is estimated to reduce the gravitational force by supporting his body weight on the holding device. Therefore, to analyse the closing moment, an additional sensor measuring Fg would be needed, or the result would be given as a function from 0-100% of body weight reduction. Furthermore, marker position changes due to skin shifts might add large error to the results of the separated moments. Usability and effect sizes are not available yet.

4 CONCLUSIONS

The Flexibility Trainer prototype is expected to have the potential to enhance the training of active and passive flexibility, even more than with CRAC-PNF methods, due to cumulated effects of combined methodical approaches (isokinetic, full-ROM strength training with CRAC), which might also last longer. Furthermore, based on the tests and component data sheets, the device should resist all expected loads without damages and meet the requirements. However, future studies are needed to proof short- and long-term functionality.

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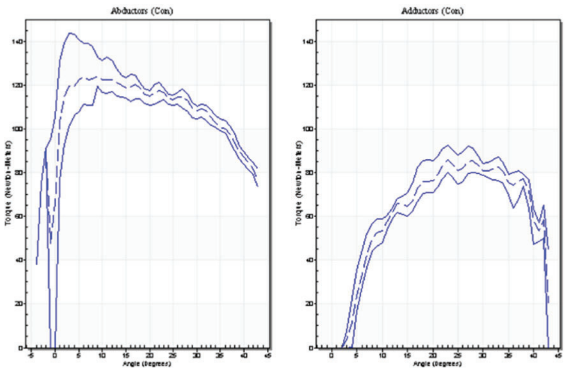
APPENDIX



Appendix A: Isokinetic hip joint adduction and abduction tests of a highly skilled Martial Artist with a height of 1.82m and a weight of 78kg on a Humac® CSMI device.

14. Publication 5: Acute Response on general and sport specific Hip Joint Flexibility to Training with Novel Sport Device

Publication status: The following manuscript was submitted to the Sports Biomechanics Journal at the 12/12/2020 (Hoelbling, Grafinger, et al., 2020 Review). Prof. Baca and Prof. Dabnichki contributed planning, proof-reading, and continuous assistance at the writing process to this paper. Description of components, hip moment calculations and Finite Elements Analysis was added by Prof. Grafinger. Martin Smiech and Dea Cizmic programmed a Python® code for automated analysis, based on the previous publications on the topic. Literature search, hip moment equations and manuscript writing (Introduction, parts of Results and Discussion and Conclusions), was performed by Dominik Hoelbling.

Acute Response on general and sport specific Hip Joint Flexibility to Training with Novel Sport Device

Original Investigation

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Abstract

The study objective is to test general- and sport-specific adaption during a single training on the *Flexibility Trainer*. The device is designed to trigger reciprocal- and autogenic-inhibition in the hip-joint muscles by providing (nearly) isokinetic resistance during a full range of motion strength training in adduction/abduction and flexion/extension direction.

Static hip flexion and abduction as well as kinematics of double side kicks were analysed on 15 participants before and after training (or rest for controls) to assess general flexibility and sport-specific movement range. Tests were recorded by a Vicon® motion capturing system. Static hip flexion and abduction as well as leg vector spreading angles (VSA) at different nodes of the kick were selected to determine adaptions of active and passive flexibility. Normalized hip joint moments, movement velocities and VSA were calculated to evaluate the training with the device. ANOVAs with 4-repeated measures and Friedman tests were performed to identify time differences and Bonferroni post-hoc test to identify between-subject effects.

Significant differences were found for both static flexibility tests (Flexion=13.65%; Abduction=10.00%) and the VSA at specific action phases (≤15.15%).

Results indicate that short-term adaptions when training with the *Flexibility Trainer* are exceeding comparable literature showing improved flexibility and sport-specific performance.

Keywords: Range of Motion; Strength; Martial Arts; Sports Engineering; Proprioceptive Neuromuscular Facilitation

Introduction

Flexibility, as “the ability to move a joint smoothly through its complete range of motion … is determined by the nature of the joint structure, the condition of the ligaments and fascia that surround the joint, and muscle extensibility” (Kent, 2006, p. 214), whereas active flexibility additionally depends on antagonistic muscle strength. However, joint stability decreases with the reduction of residual muscle tone, which increases injury risk (Chumanov, Heiderscheit, & Thelen, 2007). Therefore, strength and flexibility in combination with sufficient joint stability constitute essential synergizing abilities for certain sport techniques. Particularly hip joints determine movement stability in various sports (Rahman & Islam, 2020) as their active range of motion (ROM) is a particularly important performance parameter. For example, martial artists need superior hip joint flexibility and strength, while performing kicking techniques at chest/head level of their opponents (Hölbling, Preuschl, Hassmann, & Baca, 2017). Furthermore, flexibility significantly decreases with age and periods of immobility (Roaas & Andersson, 1982), which renders active hip joint ROM training challenging, particularly for adult athletes. Recent research established four methodical approaches (2 reflexes, namely autogenic and reciprocal inhibition; serial hypertrophy as physiological adaption; isokinetic training mode) that may support the effectiveness of this type of training (Brown, 2000; Csapo, Alegre, & Baron, 2011; Kent, 2006, p. 62; 458; Sharman, Cresswell, & Riek, 2006).

Autogenic inhibition (or inverse myotatic reflex) defines a ”reflex inhibition of a motor unit in response to excessive tension in the muscle fibres it supplies” (Kent, 2006, p. 62), meaning that after a maximum contraction, a muscle is forced, i.e. lower the residual tension. This is “attributed to the increased inhibitory input arising from Golgi tendon organs (GTOs) within the same muscle” (Sharman et al., 2006). Therefore, the reflex is used to force significant short-term adaptions in ROM. Reciprocal inhibition is “a process that inhibits the stretch reflex in antagonistic pairs of muscles. When one muscle contracts it sends inhibitory nerve impulses to its opposing muscle causing it to relax" (Kent, 2006, p. 458). Both reflexes combined are used in a special form of proprioceptive neuromuscular facilitation (PNF), called contract-relax-agonist-contract (CRAC) training, which appears extraordinarily effective for short-term training adaptions (Sharman et al., 2006). Furthermore, recent studies show that full ROM strength training results in physiological adaptions of muscles and fascias related to flexibility improvement (Baker, Wu, Green, & Caiozzo, 2006; Csapo et al., 2011; Franchi et al., 2014; Reid & McNair, 2004). This physiological adaption is called serial (or longitudinal) hypertrophy. In this process, additional sarcomeres are produced to ultimately increase the muscle length and therefore, it counts as a long-term flexibility enhancement method. Berne, Levy, and Koeppen (2008) concluded that contraction velocity and shortening capacity increase by the same fraction as the muscle length, whereas force remains unchanged. The training device presented in this work is designed to trigger this effect. To ensure safe and effective exercise, force-independent strength training with constant velocity is considered advantageous in comparison to ballistic movements (particularly when gravitational force is involved) that could lead to damage of joint structures and excessive physical resistance. Furthermore, maximum voluntary contraction in all joint angles might bring about better improvements (Brown, 2000, p. 175) during full ROM strength training.

As stated above, a combination of all 4 methodical approaches is believed to result in superior adaptions of flexibility and strength, particularly if combined in one sports device for targeted semi-isolated training. Therefore, a sports device prototype, called *Flexibility Trainer* (FT) based on the concepts by Hölbling (2016) was manufactured for testing. Based on the preliminary design published by Hölbling, Grafinger, Baca, and Dabnichki (2020), a working prototype was produced for the study. The device consists of an aluminium U-profile (Figure 1, no. 1), with a linear guide (2) for the sliders (3) inside. A radial damper (4) is mounted on the slider's baseplate to reduce the rotational velocity of the horizontal foot mount (5) axis (6), to prevent ankle injuries. The foot mounts can also be rotated on the longitudinal axis (7) to enable both front and side split training. Both slides are connected (on opposite sides) to a steel cable (8), circling alongside the device between 2 bearings (9), in order to ensure synchronous motion for both legs. The near-isokinetic deceleration is provided by two serial (ACE HB-40-P) hydraulic dampers (10), which are connected to one slide, with a (U9c) force sensor (11) in between. Furthermore, the U-profile is extended by 2 handle mounts (12) as bases for the U-formed front (13) and straight rear handle (14), to enable weight distribution and stability for side and front split training.

[Figure 1 near here]

The device is designed to enhance both general and sport-specific ROM, by increasing active and passive flexibility as well as strength. Its effectiveness needs to be tested using common sport motoric tests as well as a sport specific technique analysis, which highly depends on hip joint flexibility to test the effectiveness of the device. Both are based on the paper by Hölbling, Baca, and Dabnichki (2020a), which analyses correlations between 2 static flexibility tests (standing toe touch and sitting side split) with leg vector spreading angles (VSA) during the double side kick (DSK) kicking combination. Results indicated that the movement range during the DSK execution is highly related to the static hip abduction flexibility, as well as the overall performance of the kick and tournament success of the fighter. For sport-specific testings, the double side kick proved to constitute a frequently used and sufficiently researched martial arts competition technique combination (Ouergui, Hssin, Franchini, Gmada, & Bouhlel, 2013; Siska & Brodani, 2017). The fact that it is a single-leg double kick but still a very common competition technique ranks it as one of the most difficult 'standard' techniques, which renders it ideal for distinction between skill levels. The technique is executed from a double foot jumping movement (BNC) called ‘bouncing’ (Young-Kwan & Yoon Hyuk, 2011) or ‘hopping’ (Yuncza, 2011). After a short initiation action (PRE, between nodes LJ and INI), the total kicking movement (TKIM) starts with a lateral pendulum-like front leg elevation (CH1, between nodes INI and MT1). During this movement, a knee flexion (FLX1) is performed to decrease the lever arm of the kicking leg. Afterwards, the leg is extended again, which leads to the first kicking action (KI1, between nodes MT1 and KE1) without target contact. It can be stated that more successful technique executions are characterized by a higher leg elevation and spreading angle (Hölbling, Baca, et al., 2020a) in these phases. After maximum knee extension, a second leg elevation (CH2, between nodes KE1 and MT2), with another knee flexion (FLX2) and second kick (KI2, between nodes MT2 and KE2) with target contact are executed, which constitutes the end of KIM2 and consequently TKIM. The quality criteria of KIM2 are rather characterized by horizontal movement speed (Hölbling, Baca, & Dabnichki, 2020b). Finally, the kicking leg is restored on the floor (END, between nodes KE2 and FC). Detailed phase and note definition was used from Hölbling et al. (2017) and Hölbling, Baca, et al. (2020b) and is illustrated in Figure 2.

[Figure 2 near here]

The aim of the study is to analyse the general and sport-specific short-term responses to a training with *The Flexibility Trainer*. This objective leads to following hypotheses:

1) The training with *The Flexibility Trainer* results in a significant improvement of hip flexion during the standing toe-touch test.
2) The training with *The Flexibility Trainer* results in a significant improvement of hip abduction during the sitting side split test.

3) The training with *The Flexibility Trainer* results in a significantly higher leg spreading angle during specific nodes (INI; FLX1; MP1; KE1; FLX2; MP2; KE2; FC) of the DSK technique execution.

Materials and Methods

Experimental Approach

The laboratory was equipped with a $3x1m^2$ tatamis (martial arts mats) with a punching bag at the end of the technique execution area and a $3x2m^2$ tatami with wooden panels on it as the foundation for *The Flexibility Trainer* as suggested by Hölbling, Grafinger, et al. (2020). The entire motion analysis volume was surrounded by 12 infrared Vicon® 3D motion capturing cameras. During the tests and device training, the participants were equipped with 39 reflective markers, which were placed on specific landmarks on the body according to the plug-in-gait marker setup (Vicon®, 2016). The marker positions within the observation volume were digitalized and labelled, using Vicon® Nexus. After recording, data was prepared (filling gaps) and smoothed, using Woltring filter routine (Woltring, 1986) for markers and a Butterworth filter with 1 Hz cut-off frequency (due to long and slow motions) for force sensor data (Winter, 2009), for performance analysis during device training (see Equation 2 and Equation 3). Then, plug-in-gait static and dynamic gait models were applied, to establish joint angles and joint centre positions. Data was extracted, using specially developed Python® routines for unification of the data extraction process, and exported into Microsoft Excel.

Subjects

The sample group consisted of 15 low to high achieving male martial artists (kickboxing, sport karate and taekwondo), including 2 world championship finalists and (additionally) 6 national champions. Each fighter participated in both the control (first test day) and the training group (second test day) at 2 different days within 1 week at a similar daytime. Participants (Age:

30.13years ±6.97; Mass: 84.93kg ±10.55; Height 182.27cm ±4.58) were healthy, without current or chronic hip or knee joint pain, and each of them had at least 1 year of experience in their sport.

Procedures

After their declaration of informed consent (approved by the ethics committee), the athletes were instructed to do a standardized warm-up, consisting of 5 minutes of cycling at 60-80 watts on an exercise bike and 2 different types of hip-joint swing gymnastics (20 repetitions of lateral and front swings with straight and bended knee), followed by the marker placement for the Vicon® motion capturing analysis. The testing procedures started with the standing toe-touch test for the assessment of hip flexion (Kippers & Parker, 1987) and the sitting side-split (Amigó, Faciabén, Marginet, Ferrer, & Evrard, 2010) test for hip abduction.

After a short break, 3 trials of 3 repetitions of the double side kick were performed. Participants were instructed to reach the target at chin height at the second kick, however, lower kick heights were also accepted for analysis. If markers detached during the trial, the participant was instructed to stop and perform another full trial after replacement. Incomplete or insufficient trials (e.g., if the first kick was not fully performed) were excluded from the analysis.

For the device training, athletes were instructed to wear shoes, and foot markers were placed accordingly, so the participants' feet could be fixed to the foot mounts of the sliders. The training started with the abduction position shown in Figure 1, no. 6. The athlete performed the exercise, as described in Tables

Table 1. After another short rest of about 2 minutes the participants executed the training in both front split directions (Figure 1, no. 6) in the same sequence, with another 2 minutes of rest in between.

[Table 1 near here]

The exercise sequences were followed by 15 minutes of rest for the control group testing day, in order to exclude a possible test-habituation effect or any effects from the kick exercise on the flexibility tests and vice versa. After the training, athletes were instructed to take off their shoes, and markers were placed accordingly. The post-exercise (or rest) flexibility and (3 trials of 3) double side kick tests were repeated in the same sequence as in the pre-exercise (or rest) tests on both testing days (control and training).

Variable definition

To analyse both general and specific flexibility before and after the intervention (or rest) as well as to describe the device training modalities, a specific set of variables was established for each test.

Static flexibility test data: To identify changes in static hip flexibility, the combined abduction angles of both hip joints and the maximum average of right and left hip flexion angles, as given by Vicon®, were chosen for analysis.

Double side kick technique execution

To analyse sport-specific changes in dynamic flexibility through device training, the leg vector spreading angle (VSA; angle between vectors from hip to ankle joint centres of both legs) was calculated, using Equation 1, according to Hölbling, Baca, et al. (2020a):

$$\varphi \;=\; (\cos^{-1}\left(\frac{\overrightarrow{LL}\,.\,\overrightarrow{RL}}{\left|\overrightarrow{LL}\right|\cdot\left|\overrightarrow{RL}\right|}\right))$$

Equation 1: Maximum leg vector spreading angle (VSA) calculation for each spreading repetition at device training. φ= Leg vector spreading angle; LL= Left leg vector angle; RL= Right leg vector angle (Figure 3).

Device Training data: To determine the physical performance during the device training, the average relative hip joint moment during the spreading and closing motion, on the basis of force sensor data and Vicon® plug-in-gait model outputs (Vicon®, 2016), we used the equations outlined below (all scalars):

- Cumulated hip spreading moment (M_{hSp}), based on Figure 3, was calculated by subtracting the gravity component from the sensor force and translating it to the hip, using Equation 2, as described in Hölbling, Grafinger, et al. (2020):

$$M_{hSp} = \frac{|F_s| - {}^{1}\!/_{2}\, F_g \cos \propto}{\cos(90-\propto)}\; l_{leg}$$

*Equation 2: Calculation of leg spreading hip moment during device training. Legend: M_{hSP}= Hip joint spreading moment; F_S= Sensor Force (for 1 leg); F_g= Gravitation force (m*g); α= Leg/floor angle; l_{leg}= Leg length.*

[Figure 3 near here]

- In contradiction to the above, for the closing movement, the gravity component is added to F_s. However, it is not known how much of the participants' weight is supported on the handles. Therefore, a range between 50% and 100% was chosen as compensation for missing data. Equation 3 was used for this calculation:

$$M_{hCl(R_{Fg})} = \frac{|F_s| + {}^{1}\!/_{2}\ F_g \cos \propto R_{F_g}}{\cos(90-\propto)} l_{leg}$$

*Equation 3: Calculation of leg closing hip moment during device training. Legend: M_{hCL}= Hip joint closing moment; F_S= Sensor Force (for 1 leg); F_g= Gravitation force (m*g); α = Leg/floor angle; R_{Fg}= Range of gravity supporting force (0 - 0.5) l_{leg} = Leg length.*

- To calculate each component (flexion/extension, abduction/adduction, ext./int. rotation), the cumulated hip joint moment M_h was divided in the same ratio as the Vicon® model outputs, which are based on the segmental movement direction but do not include the resistance of the *Flexibility Trainer*. Equation 4 (Hölbling, Grafinger, et al., 2020) was used for this calculation:

$$M_i = \frac{M_h}{|M_{Vx}| + |M_{Vy}| + |M_{Vz}|} |M_{Vi}|$$

Equation 4: Calculation of hip flexion/extension moment. Legend: M_i= Hip joint moment in preferred movement direction (M_x= Flexion/Extension moment; M_y= Abduction/adduction moment; M_z= Int./ext. rotation moment); M_{Vi}= Vicon calculated moment in preferred movement direction; M_h= Cumulated hip moment; M_{Vx}= Vicon hip flexion/extension moment; M_{Vy}= Vicon hip adduction/abduction moment; M_{Vz}= Vicon hip int./ext. rotation moment.

- Finally, the average, relative adduction/abduction moment (for device adduction/abduction trial) was calculated separately for leg spreading and closing motion, using Equation 5:

$$\varnothing M_i = \frac{\sum|M_{ir}| + \sum|M_{il}|}{2n_{M_i}m}$$

Equation 5: Calculation of average normalized hip moment. Legend: $\varnothing M_i$= Average normalized moment in preferred movement direction (M_x= flexion moment; M_y= abduction moment); M_{ir}=Hip moments right leg (M_{xr}= flexion/extension moment right leg; M_{yr}= Abduction/adduction moment right leg); M_{il}=Hip moments left leg (M_{xl}= flexion/extension moment left leg; M_{yl}= Abduction/adduction moment left leg); n_{Mi}= Number of frames used for calculation; m= body mass.

Furthermore, average horizontal execution velocity (per leg) for both spreading and closing, as well as maximum VSA of all 3 separate executions (including rest) were determined. VSA were calculated as in Equation 1.

Statistical analysis

Statistical analysis was performed using SPSS ver. 22 (IBM Corp., Chicago, Illinois). Normal distribution for all variables was checked, using the Shapiro-Wilk test for sample size < 50 participants. Descriptive statistics of all pre- and post-tests for both groups were performed.

To identify significant differences in changes between both, training and control as well as pre and post-tests, analysis of variance (ANOVA; for normally distributed variables) for 4 repeated measures, or the Friedman test (for variables significantly differing from normal distribution) were used. Bonferroni post hoc test was used if significant differences were detected.

For all tests, a significance level of $p \leq 0.05$ was used.

Results

All 15 participants performed 2 flexibility tests each and a total of 417 kicks for all participants. ANOVA tests show significant differences in hip flexion and abduction between the test times (Table 2).

[Table 2 near here]

Furthermore, the post-test for flexion and abduction showed significant differences to all other related previous test times (Figure 4).

[Figure 4 near here]

Averaged vector spreading angles (VSA) showed significant differences between test times for MT1, KE1, FLX2, and KE2 as well as for the maxima at KIM1 and KIM2, but not for INI, FLX1, MT2 and FC, as shown in Table 2 and Figure 5.

[Figure 5 near here]

Results of Bonferroni post-hoc tests for analysis of between-subject differences of MT1, KE1, FLX2, KE2, KIM1 and KIM2 are shown in Table 3.

[Table 3 near here]

At the device training, all participants performed 3 spreading, 3 closing and 1 CRAC movement (during the last repetition) in total, for all 3 exercises. Descriptive statistics are given in Mean ±SD or Median ±IR (interquartile range) if the variable (marked with $^{+}$) differs significantly from normal distribution. To describe the performance during device training, average values for spreading velocity (v_{SpAbd}= 111.23mm/s ±23.39; v_{SpFl}= 120.64mm/s ±29.52; v_{SpFR}= 114.25mm/s ±23.75), closing velocity (v_{ClAbd}= 80.04mm/s ±11.45; v_{ClFl}= 93.71mm/s ±20.14; v_{ClFR}= 91.97mm/s ±16.18), relative spreading (M_{SpAbd}= 1.54 Nm/kg ±0.60; M_{SpFl}= 1.43 Nm/kg ±0.76; M_{SpFR}= 2.15 Nm/kg ±0.68) and closing moment (M_{ClAbd} between 1.69 Nm/kg ±0.46 and 1.61 Nm/kg ±0.44; M_{ClFl} between 1.60 Nm/kg ±0.73 and 1.56 Nm/kg ±0.71; M_{ClFR} between 1.29 Nm/kg ±0.74 and 1.26 Nm/kg ±0.73), as well as the maximum VSA ($\varphi_{maxAbd1}$= 125.12° ±15.71; $\varphi_{maxAbd2}$= 126.59° ±14.97; $\varphi_{maxAbd3}$= 125.18° ±19.35; φ_{maxFl1}= 130.19° ±12.51; φ_{maxFl2^+} = 132.61° ±11.39; φ_{maxFl3}= 133.68° ±8.31; φ_{maxFr1}= 128.25° ±11.95; φ_{maxFr2}= 131.58° ±9.01; φ_{maxFr3}= 133.74° ±8.60) for all 3 repetitions and exercises (Abduction=Abd; left front split=Fl; right front split=Fr), were calculated.

Discussion and Implications

Results clearly show that training with the *Flexibility Trainer* (FT) significantly enhances both general and sport-specific flexibility/ROM. The general flexibility tests showed average improvements of 10.1° (13.65%) for static hip flexion and 10.3° (10.00%) for combined abduction (Figure 4). In comparison, Feland, Myrer, and Merrill (2001) reported median improvements on hamstring flexibility of 4° from static and 6° from PNF training, while Sharman et al. (2006) describe an expected range of 3°-9° for one PNF treatment based on their systematic review. A comparison of the absolute values of the training groups' pre- and post-tests to the study of Hölbling, Baca, et al. (2020a) also provides interesting insights. This study compared static flexibility of 3 groups, which could be described as absolute world elite (1), elite (2) and advanced (3) kickboxers and karateka. The current pre-test of the FT training group showed slightly lower mean values (Flx: 74.2°; Abd: 84.3°) than their advanced group (Flx: 78.53°; Abd: 110.24°), while the post-test values were higher (Flx: 84.3°; Abd: 118.3°), partially even close to the mean values of their elite group (Flx: 86.6°; Abd: 132.59°). Furthermore, significant differences were found between the post tests of the training group to all other test times, while no differences were found between the other test times. In fact, all participants improved both static hip joint flexibility components after the training with the *Flexibility Trainer*, which leads to the acceptance of hypotheses 1 and 2.

Sport-specific movement range measured with vector spreading angles (VSA) also improved at most nodes during the double side kick execution. Mean VSA of MT1 (+7.67%), KE1 (+15.15%), FLX2 (+7.55%), and KE2 (+3.94%), as well as the maxima of KIM1 (+8.08%) and KIM2 (+3.94%), showed significant improvements, particularly within the training group, while the control group test times and the pre- test of the training group, showed no significant differences at all (Table 3). Furthermore, all these values showed significant differences between-subject effects (Table 2), which leads to the acceptance of hypothesis 3. Comparisons of these results with those from the 3 groups of Hölbling, Baca, et al. (2020a) showed that the FT training caused slightly lower maximum angles before (114.9°) and slightly higher maximum angles (119.4°) after the intervention than their advanced group (116.45°). These values are again just slightly below their elite group (122.35°). A different situation has been found during the kick executions, where both the pre- and post-test values are between their advanced and elite group at MT1 and KE1. Post-test values of the FT training group at MT2 are very close to those of their elite group and at KE2, the values are even above the VSA of their elite group. This may indicate that the sport-specific performance of the current study is above their advanced group and the short-term effect of the device training could improve the kicking technique even to elite level. However, to support this statement, many other factors must be taken into account.

It is further noted that traditional stretching methods often have no or even negative effects on performance of ballistic movements (Curry, Chengkalath, Crouch, Romance, & Manns, 2009; Perrier, Pavol, & Hoffman, 2011; Young & Elliott, 2001). On the contrary, the current method showed highly significant improvements due to the device training, which could either have contributed to a short-term improvement in muscle strength or solely to the decrease of antagonistic inhibition, which future studies should clarify.

To summarise, both general and sport-specific flexibility has improved more than expected after the training with the FT, by up to 15.15% on average. These effects might be based not solely on an increased reciprocal and autogenic inhibition effect, due to full ROM resistance (hip moments up to 2.15 Nm/kg on average), but also on the release of fascia bondings due to strong contractions in maximum positions and increased stress tolerance. Given the fact that improvements were found across the entire participant population, from highly flexible and highly successful martial artists to fighters with lower performance level.

Based on the rapid ROM increase during the device training, with the first execution (with 125.12° on average) already above the maximum static flexibility result (107.55° on average before the intervention) and the strong contractions throughout the exercise, we want to introduce the descriptive methodical term of *Supra-ROM strength training (SROM)* for this exercise type. It describes a strength exercise, performed in a ROM higher than the previous static maximum.

Therefore, we conclude that the *Flexibility Trainer* is potentially an effective device to improve the hip-joint flexibility. It enables the athlete to effectively perform SROM strength training by using respective reflexes within the training session. This is expected to lead to novel training effects by forcing the targeted muscles to a serial hypertrophy and increased strength in the opposing muscles. However, the device design is work in progress and future studies need to assess long-term adaptions and optimize the training sequence. To provide an outlook on planned future research, we would expect that long-term adaptions due to a combined effect of CRAC PNF and SROM to be significantly higher than in previously reported. For example, Sharman et al. (2006) report improvements of up to 21° in 12 weeks, Rowlands, Marginson, and Lee (2003) found 33.6° in 6 weeks of CRAC training, whereas in Valamatos, Tavares, Santos, Veloso, and Mil-Homens (2018), fascia length increased by 4.9% in a 15 week intervention, and in Reid and McNair (2004), the joint angle improved by 10.1° after 6 weeks of full range of motion training.

Limitations

The device prototype requires improvement in stability, particularly at the handle constructions (side movements) and foot mounts, mainly due to tolerances of the used tools and standard parts. Furthermore, the foot mounts are not optimized for a self-training configuration.

The exact closing moment was not possible to be calculated, as the weight reduction due to handle support was not measured. Therefore, a range of expected weight reductions between 50% and 100% was chosen.

Different training sequences with the device should be tested for determining an optimum.

The results only show short-term adaptions by the device, compared to a non-training setting. A training study should be performed to analyse short- and long-term adaptions compared to other flexibility trainings with similar load durations, in order to determine cumulated benefits and advantages of a training with the device. Furthermore, some sport specific variables showed significant difference between pre- and post-test in the training group but not between control tests and post-test of the training groups, which may be due to a limited learning or adaption effect. This effect, however, didn't hold on until the next test day, as some variables decreased again until the pre-test of the training group.

Practical Implications

Training with the *Flexibility Trainer* leads to significantly higher flexibility adaptions within each training session, which is believed to consequently improve adaptions in a training period. Additionally, joint stability and antagonistic strength might be increased after FT training, whereas traditional stretching methods often lead to no or even negative effects on sport performance of ballistic movements. The training directly effects general flexibility and related sport-specific performances. Furthermore, this effect was even found in participants with a very high ROM and could therefore help to overcome performance plateaus.

Acknowledgements

The authors express their gratitude to all athletes who participated in the study and further to the students who constructed the first two versions of the *Flexibility Trainer* as well as the engineers who finally manufactured the prototype.

Declaration of Interests Statement

No potential conflict of interest was reported by the authors.

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Tables

Table 1: Flexibility Trainer exercise description for total ~60s.

Part	Duration	Exercise	Anticipated Function
1	Individual ~5s	Leg spreading (hip abduction; hip flexion/extension)	Activation of reciprocal inhibition and full-ROM strength training
2	5s	Relaxation at maximum ROM	Passive flexibility and stress tolerance training
3	Individual ~5s	Leg closing (hip adduction; hip extension/flexion)	Activation of autogenic inhibition and full-ROM strength training
4	2s	Rest	Rest
5-8	Individual ~5s	Repeating part 1-4	Same as above
9	Individual ~5s	Leg spreading (hip abduction; hip flexion/extension)	Activation of reciprocal inhibition and full-ROM strength training
10	8s	Static contraction of leg-closing muscles	Static activation of autogenic inhibition
11	8s	Static contraction of leg-spreading muscles	Static activation of reciprocal inhibition
12	Individual ~5s	Leg closing (hip adduction; hip extension/flexion)	Activation of autogenic inhibition and full-ROM strength training

Table 2: Results of within-subject effects and group differences of ANOVA (or Friedman test for variables, which significantly differ from normal distribution).

	Avg. hip flex.	**Comb. hip abd.**	**φINI[+]**	**φFLX1**	**φMT1**	**φKE1**	**φFLX2**	**φMT2**	**φKE2**	**φFC[+]**	**φKIM1max**	**φKIM2max**
p_Sphericity/ p_Friedman	<0.01*~	<0.01*	0.30	0.07~	<0.01*	<0.01*	<0.01*	0.11~	0.04*~	0.86	<0.01*	<0.01*
Willks λ/Friedman χ^2	0.33*	0.25*	3.64	0.32*	0.24*	0.44*	0.39*	0.57	0.38*	0.76	0.30*	0.29*

[+]Variable significantly differs from normal distribution

* Significant difference between groups ($p < 0.05$)

~ Greenhouse-Geisser was used due to significant Mauchly-Test and correction value <0.75

Table 3: Bonferroni post-hoc test for ANOVA for comparison of group differences of the nodes with significant ANOVA outcomes during the kick execution. Mean and standard deviation of VSA are given for each group and brackets below mark significant differences of the Bonferroni test and the respective test times.

	Control_Pre	Control_Post	Training_Pre	Training_Post
φMT1	83.88°	86.69°	85.69°	92.26°
	±14.49	±15.01	±11.42	±12.75
		p<0.01		
			p<0.01	
φKE1	72.95°	76.98°	74.89°	86.24°
	±17.83	±19.05	±17.37	±16.87
		p<0.01		
			p=0.01	
			p<0.01	
φFLX2	89.32°	91.07°	89.16°	95.89°
	±12.99	±14.93	±11.75	±11.97
		p=0.02		
			p<0.01	
φKE2	112.52°	112.96°	113.12°	117.58°
	±9.52	±9.96	±7.86	±6.85
			p<0.01	

Figures

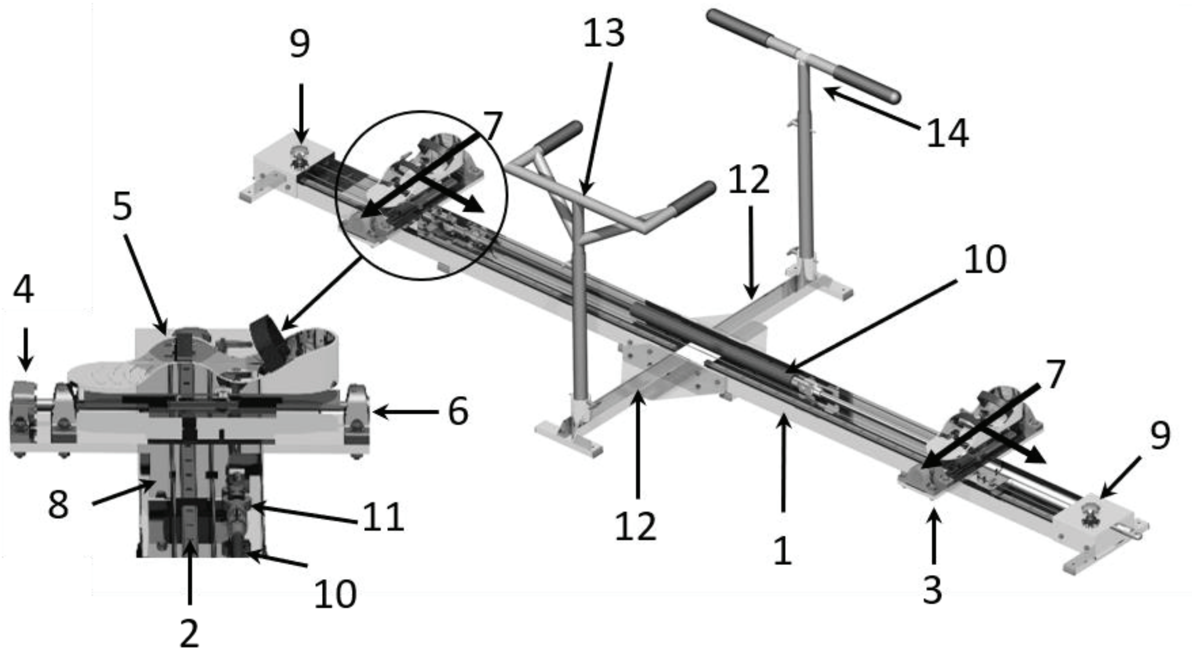

Figure 1: Design illustration of Flexibility Trainer, with the braking system (isokinetic hydraulic dampers) and the force sensor (connection between dampers and left slide). Rotational damper (front of foot mount), steel cable with guide rollers (from left to right and its opposing sided mounts on the sliders (Hölbling, Grafinger, et al., 2020). (1) U-profile; (2) Crossbeam; (3) Stabilizers; (4) Handles; (5) Rotation (tilt) axis; (6) Foot position adjustment.

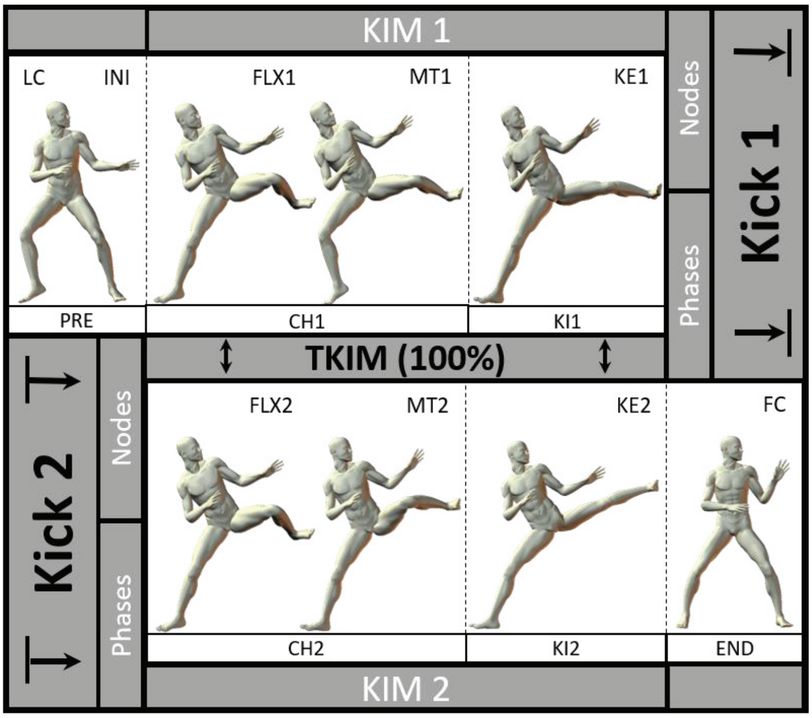

Figure 2: Phases and Nodes illustration of the double side kick, with specifications of kicking movement 1 and 2 (KIM1; KIM2), which together forms the total kicking movement (TKIM) and also the 100% for relative phase calculation.

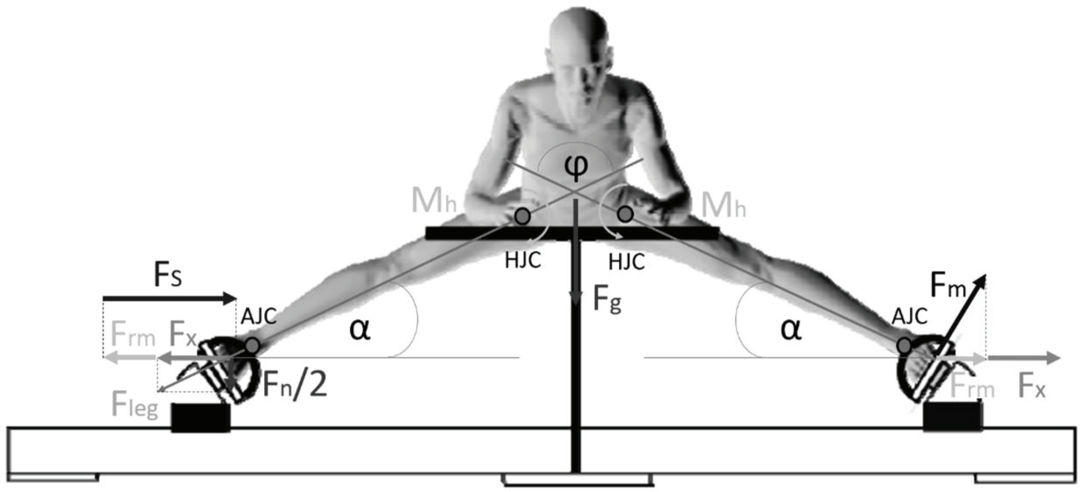

Figure 3: Illustration of forces and moments acting during device training, adapted from Hölbling, Grafinger, et al. (2020).

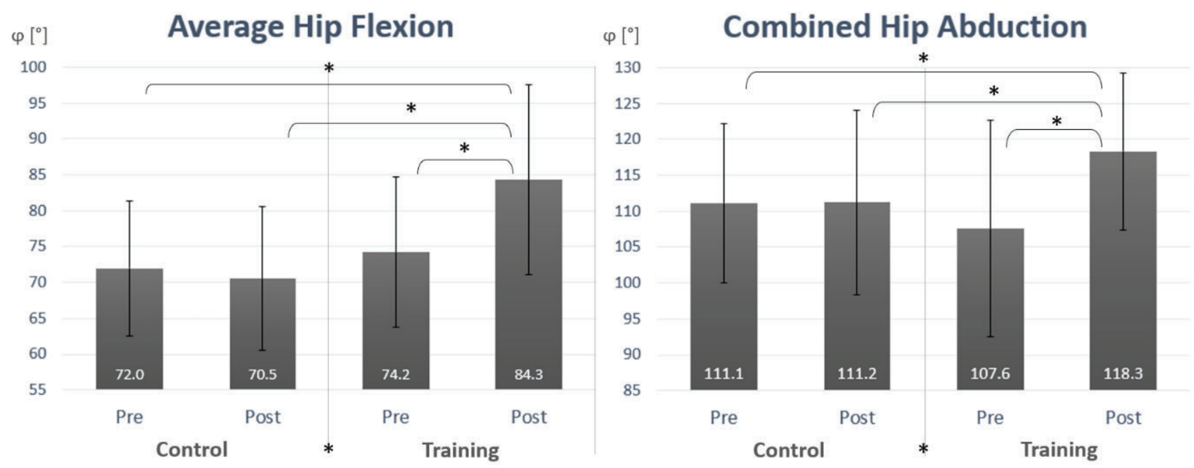

*Figure 4: Static flexibility test results training (TR) and control (CO) group before (Pre) and after (Post) intervention or rest. * above bars marks significant differences of Bonferroni post-hoc test between test times, whereas * between the bars on the bottom means significant difference of the ANOVA test between test times (further details in Table 2).*

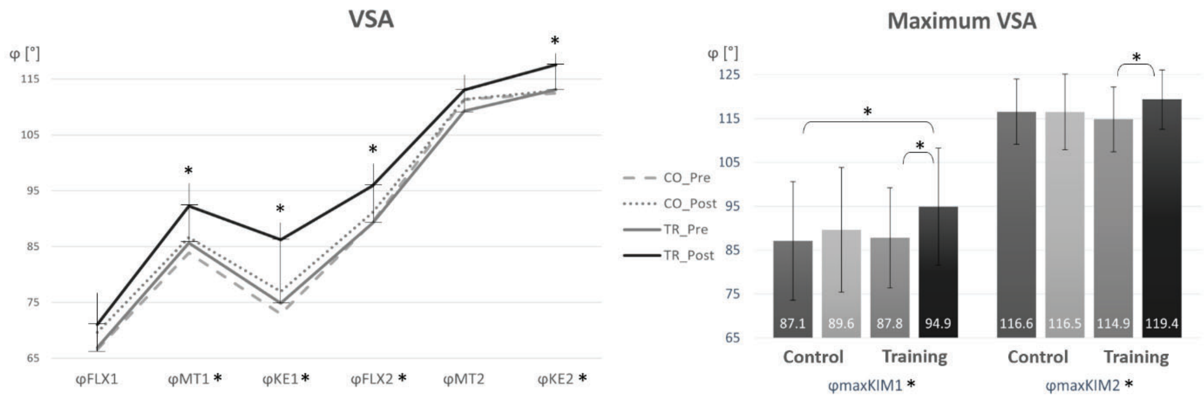

*Figure 5: Results for Vector spreading angles (VSA) during the kicking movements (KIM) of training (TR) and control (CO) group before (Pre) and after (Post) intervention or rest. * marks significant differences between variables and groups (further details to group differences for VSA at the nodes are shown in Table 3).*

Figure Captions

IV. Discussion

Based on the general aim of the dissertation, which (in short) was to develop a training device for the enhancement of kicking techniques in Martial Arts, a two staged approach outlined in 5 publications was conducted. The first stage consists of 3 papers exploring different existing and novel methods for kick technique analysis, to gain comprehensive knowledge on performance-relevant kinematic parameters. Summarized, it can be stated that kick technique performance is highly related to strength and flexibility of hip joint muscles, which confirmed the preliminary expectations outlined in the Introduction. Therefore, the second stage was devoted to design, manufacture and test a sport device for the enhancement of these physiological pre-requisites for successful kicking. While detailed outcomes for each approach can be found within the publications (section 10- 14), the following cumulated explanation is aimed to provide a clear red line throughout the general topic.

15. Kicking technique analysis

Kicking technique analysis clearly showed that a variety of factors must be considered to lead to high performance. Publication 1 (section 10) outlined a complex series of power generation including 2 proximal-to-distal movement sequences combined with a leg-elevation deceleration, which might contribute to both, distance reduction to the target (supporting leg slide) and general power output to the target (see, Figure 21).

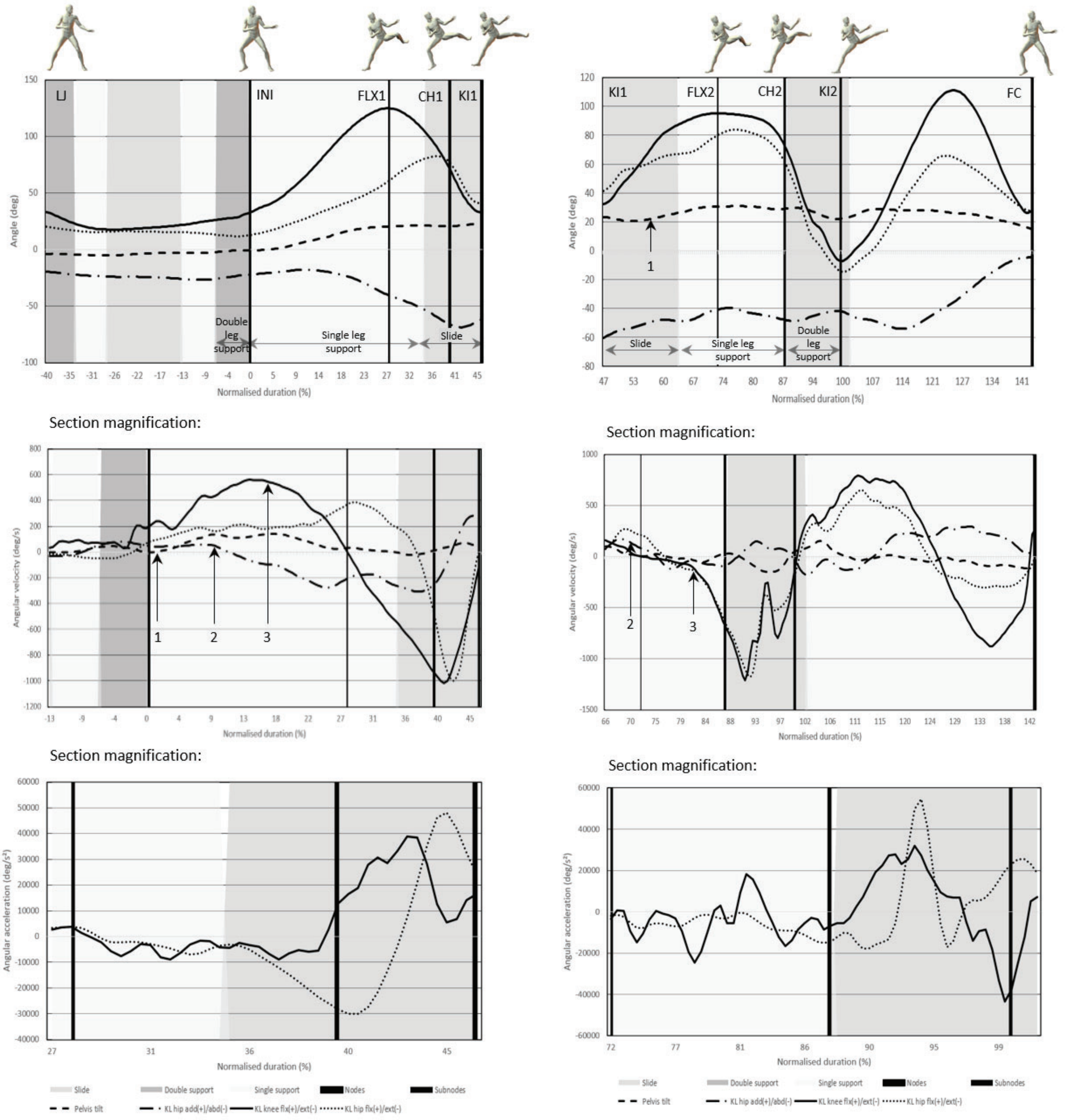

Figure 21: Kicking leg (KL) angles, angular velocity, and angular acceleration for the 1st kick (left) and the 2nd kick (right). The proximal-to-distal movement sequences (PDMS) are marked (1) pelvis tilt, (2) hip abduction and (3) knee extension.

Furthermore, these sequences are carefully coordinated with a dynamically balanced single leg-supported movement of the SL (see, Figure 22). Both aspects not solely show the complexity of the analysed technique but also comprised significant differences between success groups, which determines the importance of the underlying physiological parameters.

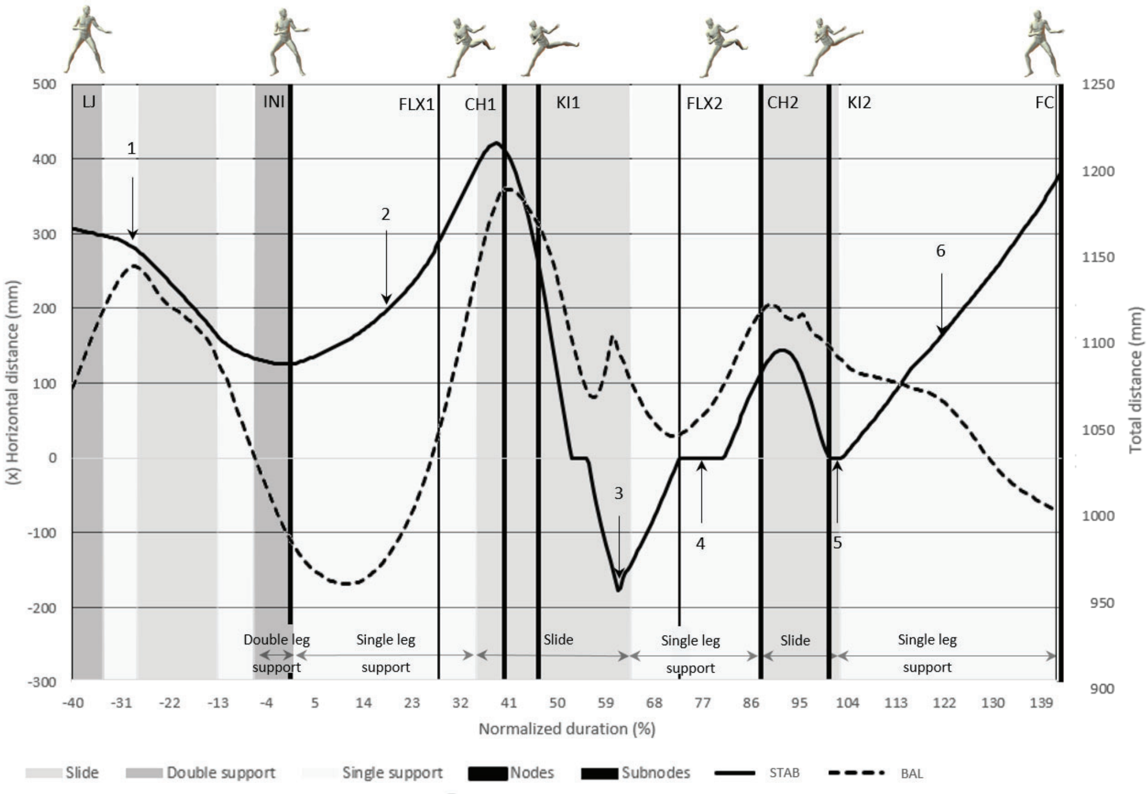

Figure 22: STAB and BAL of a representative participant during the PRE phase, TKIM, and END including marks of special events. (1) is based on a reclining movement of the thorax, which is part of the initial movement, (2) marks the leg elevation of kicking leg in combination with a push movement of the supporting leg, (3) shows the end of the slide movement, which brings the supporting leg in front of the COM in order to prepare the full support (4) after the rest of the body reaches the supporting leg due to its horizontal movement. (5) marks the leaning forward movement of the trunk during the set down of the kicking leg

In a next step (section 11) rather small pre-kick execution movements, called initiation actions (or Telegraphs, when their amplitude was large enough to potentially be detected by an opponent) where assessed for their mechanical function and their treacherous potential to the opponent. Results indicated that the different movements serve two biomechanical functions, namely an up-unweighting (Müller, 1994) or COM elevation (CET) and a weight re-distribution (WRT) for attaining the supporting conditions to ease the leg elevation. These movements, while potentially dangerous as they can provide the opponent with more time for counteractions, are necessary to initiate the technique. However, it is further stated that initiation actions with lower amplitude and happening later (relative to leg elevation) might be advantageous. Therefore, combining the outcomes of publication 1 and 2, it is expected that increased strength and flexibility in the hip joint decreases the necessity of unsubtle preparatory movements. However, studies with large samples, due to very small differences in motion would be needed to confirm the statement.

The final technique analysis paper (section 0) was conducted to particularly analyse the main output factor consequently arising from the previously discussed parameters, namely sub-maximal ROM, or movement range during technique execution as well as its pre-requisite static hip joint flexibility. Results clearly showed that kicking performance is highly related on both static flexibility and movement amplitude during the technique execution. Summarized, hip joint flexibility and strength proved to be essential components of successful kick executions.

16. The Flexibility Trainer

Therefore, a sports device was established specifically targeting these physiological pre-requisites by a combination of 4 state-of-the art methodical approaches, namely activation of autogenic and reciprocal inhibition, full range of motion and isokinetic strength training strength training. General design applications, underlying framework conditions for essential components and an appropriate test setup was proposed in publication 4 (section 14). A simplified prototype was manufactured, adapted to increase participant safety, and prepared to test of short-term adaptions after device training. It worked with nearly constant velocity with a standard deviation of less than 30% from average velocity, which leads to the acceptance of hypothesis 1 of the dissertation. The outcomes of a pre- and post-training test design with control group, were beyond expectations and predictions from comparable literature (publication 5; section 14). Furthermore, significant adaptions in both, general flexibility and sport specific motion amplitude were found, which led to the acceptance of hypothesis 2 and 3. These over proportionated improvements in combination with the measurements during the device training led to the introduction of a new methodical term for this specific type of training, namely supra range of motion (SROM) strength training. It describes a training, which is predominantly performed with a significantly higher ROM, than the previous maximum. With regards to force-length relation of a muscle, described in

Section 2.3.3.4 it is noted that the isokinetic mode can be very advantageous for strength improvement in the hip joint, particularly in with respect to the hip moment graph, described in Section 13. Furthermore, ~0.1m/s movement velocity could be translated in about 5-20% of maximum movement velocity, which according to the force-velocity relationship, described in Section 2.3.3.5 complies to 40-75% of the maximum static contraction force might be a beneficial speed for a training for maximum strength (between muscle hypertrophy and intramuscular coordination. This further leads to a training recommendation of between 1 and 3 sets of 3-6 repetitions with maximum voluntary contraction and a CRAC sequence at the end, for each movement direction. However, further research is needed to clarify efficiency of different trainings.

17. Limitations

This dissertation covers several areas with partially very little published research. Three new models for technique analysis (STAB, BAL and VSA) and 1 new model for hip joint moment calculation during the training with the flexibility trainer was developed. The downside clearly is that a significant amount of research is needed to confirm the statements arising from it and further increase the application areas. Furthermore, reference values of other athletes are barely existing, which makes it hard to compare these outcomes and consequently to legitimise the models.

18. Outlook

Both, the technique analysis models and the training with the Flexibility Trainer offer substantive challenges for future research. Balance and stability indicators as well as vector spreading angles could for example be used to compare kicking techniques from different Martial Arts, while the Flexibility Trainer could be a gamechanger regarding effectiveness of hip joint flexibility training. As an example, we would expect that long-term adaptions due to a combined effect of CRAC PNF and SROM to be significantly higher than in previously reported. For example, Sharman et al. (2006) report improvements of up to 21° in 12 weeks, Rowlands et al. (2003) found 33.6° in 6 weeks of CRAC training, whereas in Valamatos et al. (2018), fascia length increased by 4.9% in a 15 week intervention, and in Reid and McNair (2004), the joint angle improved by 10.1° after 6 weeks of full range of motion training.

V.Literature

Dissertation Publications

Hoelbling, D., Baca, A., & Dabnichki, P. (2020a). A Kinematic Model for Assessment of Hip Joint Range-of-Motion in Fast Sport Movements using Spreading Angles. *Sports Biomechanics*. doi:10.1080/14763141.2020.1795237

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VI. List of figures

VII. List of tables

VIII. Appendix

Appendix A: List of abbreviations.

Abbreviation	Explanation
ANOVA	Analysis of variance
BAL	Balance indicator
CET	Centre of mass elevation Telegraph
CO	Control group
COM	Centre of mass
COP	Centre of pressure
CRAC	Contract-Relax-Agonist-Contract
CRHR	Contract-relax-hold-relax
Dec	deceleration
DSK	Double side kick
EMG	electromyography
FDM	Fused deposition modelling
FEA	Finite element analysis
FEM	Finite element method
FT	Flexibility Trainer
GTO	Golgi tendon organs
H-Reflex	Hoffman Reflex
HT	Hypertrophy training
IC(T)	Intramuscular coordination (training)
IQR	Interquartile range
KL	Kicking leg
KO	Knock out
Max	Maximum
Min	Minimum
MMA	Mixed Martial Arts
MoRa	Movement range
OM	Opposing muscle
PDMS	Proximal-to-distal movement sequence
PNF	Proprioceptive neuromuscular facilitation
Sd	Standard deviation
SL	Supporting leg
STAB	Stability indicator
TG	Telegraph
TM	Targeted muscle
TR	Training group
VSA	Vector spreading angle
WRT	Weight redistribution Telegraph
(S)ROM	Supra range of motion
1RM	One repetition maximum

Anatomy	
HJC	Hip joint centre
KJC	Knee joint centre
AJC	Ankle joint centre
os(sa)	Bone(s)
m	Muscle
FLX	Flexion
EXT	Extension
ABD	Abduction
ADD	Adduction
(int.;ext.)ROT	(Internal; external) rotation
RF	Right femur vector
LF	Left femur vector
RL	Right leg vector
LF	left leg vector
Functional phases and Nodes of the double side kick	
(T)KIM(1;2)	(Total) kicking movement (1;2)
BNC	Bouncing phase
LJ	Last jump node
PRE	Preparation phase
INI	Initiation of first kicking leg elevation
CH(1;2)	Chambering phase (1;2)
FLX (1;2)	Knee and hip flexion node (1;2)
Slide(1;2)	Supporting leg slide (1;2)
MT(1;2)	Measuring time node (1;2)
ITS(1;2)	Impulse transfer start node (1;2)
ITE(1;2)	Impulse transfer end node (1;2)
KI(1;2)	Kicking phase (1;2)
KE(1;2)	Knee extension node (1;2)
END	Restoring kicking leg to floor phase
FC	Floor contact node
Federations	
AIBA	Amateur Boxing Association
ISKA	International Sports Karate Association
ITF	International Taekwondo Federation
NASKA	North American Sports Karate Association
UFC	Ultimate Fighting Council
WAKO	World Association of Kickboxing Organizations
WBA	World Boxing Association
WBC	World Boxing Council
WKF	World Karate Federation
WT(F)	World Taekwondo (Federation)

Appendix B: Exemplary sport devices for flexibility training on the market

Device category	Illustrations	Source
Rigid straps		Stand (2020)
Flexible straps		Stretch (2020)
Foam Rollers		ProsourceFit (2020)
Passive positioning devices	 	Machine (2020); ProStretch (2020)
Active positioning devices		Fitness (2020)

Appendix C: Decision of Ethics Committee for kinematic analysis of the double side kick at the University of Vienna.

Beschluss der Ethikkommission Decision of the Ethics Committee	universität wien Ethikkommission

Antragsteller/Applicant: **Univ.-Prof. Dipl.-Ing. Dr. techn. Arnold Baca**
Bearbeitungsnummer/Reference Number: **00061**
Projekttitel/Title of Project: **Biomechanische Bewegungsanalyse eines „Doppel-Seitwärtsfußstoßes" im Pointfighting, Kickboxen.**

Die Stellungnahme der Ethikkommission erfolgt aufgrund folgender eingereichter Unterlagen/
The decision of the Ethics Committee is based on the following documents:

- Antragsformular_v1_0_2014_01_28
- Teilnehmerfragebogen_v1_0_2014_01_28
- TeilnehmerInneninformation_und_Einwilligungserklaerung_unter18_v1_0_2014_01_28
- TeilnehmerInneninformation_und_Einwilligungserklaerung_v1_0_2014_01_28
- Zusaetzliche_Informationen_zum_Ethikantrag_v1_0_2014_01_28
- Antragsformular_v1_1_2014_03_26
- TeilnehmerInneninformation_und_Einwilligungserklaerung_unter18_v1_1_2014_03_26

Die Kommission fasst folgenden Beschluss (mit X markiert)/The Ethics Committee has made the following decision (marked with an X):

☒ Zustimmung: Es besteht kein ethischer Einwand gegen die Durchführung der Studien/
Consent: there is no ethical objection to any accomplishments of the project

☐ Negative Beurteilung: Der Antrag wird von der Ethikkommission abgelehnt /negative evaluation: the proposal is refused by the Ethics Committee

Unterschrift/Signature | Datum/Date

26.03.2014

Vorsitzende der Ethikkommission/Chairwoman of the Ethics Committee
emer. o. Univ.-Prof. Dr. Ilse Kryspin-Exner

Appendix D: Ethics Committee decision for the Flexibility Trainer research at the University of Vienna.

Beschluss der Ethikkommission Decision of the Ethics Committee	universität wien Ethikkommission

Antragsteller/Applicant: **Hölbling Dominik, MSc, Bakk.**
Bearbeitungsnummer/Reference Number: **00457**
Projekttitel/Title of Project: **Comparison of biomechanical derivatives between martial arts kick technique executions and training with the "Flexibility Trainer"**

Die Stellungnahme der Ethikkommission erfolgt aufgrund folgender eingereichter Unterlagen/ The decision of the Ethics Committee is based on the following documents:

13.05.2019

- Antragsformular_Ethikkommission
- TeilnehmerInnenfragebogen
- TeilnehmerInneninformation_und_Einverständniserklärung
- Zusaetzliche Informationen zum Ethikkommissionsantrag

03.07.2019

- Antragsformular_Ethikkommission
- CoverLetter
- TeilnehmerInneninformation_und_Einverständniserklärung

Die Kommission fasst folgenden Beschluss (mit X markiert)/The Ethics Committee has made the following decision (marked with an X):

☒ Zustimmung: Es besteht kein ethischer Einwand gegen die Durchführung der Studien/ Consent: There is no ethical objection to conduct the study as proposed

☐ Negative Beurteilung: Der Antrag wird von der Ethikkommission abgelehnt /Negative evaluation: The proposal is rejected by the Ethics Committee

Unterschrift/Signature

ETHIKKOMMISSION UNIVERSITÄT WIEN

Datum/Date
15.07.2019

Stellvertretende Vorsitzende der Ethikkommission/Deputy Chair of the Ethics Committee
ao. Univ.-Prof. MMag. Dr. Sylvia Kirchengast

IX. Zusammenfassung

Leistungsfähigkeit in Kampfsportarten ist von einer Vielzahl von physiologischen und technischen Fähigkeiten abhängig. Dabei kann gezieltes, isoliertes Training der Leistungsstrukturen signifikante Verbesserungen der spezifischen Leistungsfähigkeit hervorrufen. Folglich kann die Entwicklung von darauf abgestimmten Sportgeräten die weitere Leistungsentwicklung signifikant unterstützen. Um dies bestmöglich umzusetzen ist jedoch multidisziplinäres Wissen über derzeit erfolgreiche Technikausführungsvarianten, Trainingsmethoden, sowie Maschinenbau notwendig. Das Ziel dieser Dissertation ist daher, auf Basis einer umfangreichen biomechanischen Kicktechnikanalyse, ein Gerät zur Verbesserung allgemeiner und sportspezifischer Leistungsfähigkeit zu entwickeln und zu testen.

Die kumulative Dissertation beinhaltet fünf Publikationen, wobei die ersten beiden die Applikation von zwei literaturbasierten (Funktionsphasenanalyse und proximal-nach-distal Bewegungssequenzen) und zwei neu entwickelten (Gleichgewichts- und Stabilitätsindikatoren und zur Erkennung von Ansatzbewegungen) Modellen behandeln. Darauf aufbauend wurden in der 3. Forschungsarbeit zwei weitere Modelle entwickelt, welche auf Vektor-Spreizwinkeln (VSA) basieren und eine relativ genaue Einteilung in Leistungsklassen ermöglichen. Die beiden finalen Arbeiten beschreiben die Entwicklung und Testung des Sportgerätes, mit dem Namen „Beweglichkeitstrainer“, welches zur Verbesserung der Hüftbeweglichkeit und -kraft eingesetzt werden soll und innerhalb der EU patentiert wurde.

Die Studien zeigten signifikante Korrelationen oder Gruppenunterschiede (nach Leistungsfähigkeit) bei Funktionsphasenanalyse, Geleichgewichts- und Stabilitätsindikatoren und spezifischem Bewegungsumfang in verschiedenen Phasen der Technikausführung, sowie der statischen Beweglichkeit. Das Gerät wurde mittels Pre- und Postuntersuchung von allgemeinen und sportspezifischen Leistungsindikatoren, vor und nach einer Trainingsintervention, bestehend aus drei Übungen à drei Wiederholungen, getestet. Die Verbesserung der allgemeinen Beweglichkeit und des spezifischen Bewegungsumfanges während der Kickausübung überstiegen die Erwartungen, sowie die Aussagen aus vergleichbarer Literatur. Daher wird davon ausgegangen, dass das Gerät eine wesentliche Effektivitätssteigerung zum Stand der Technik darstellt.

X. Abstract

Winning performance in Martial Arts requires a variety of physical, physiological and technique abilities. Targeted, isolated training of the relevant body structures often significantly increases sport performance. Therefore, sports equipment specifically developed for specific requirements can be very beneficial. However, it requires multi-disciplinary insights to facilitate state-of-the-art techniques, training methods and engineering know-how. The aim of the study is to establish sufficient knowledge of Martial Arts kicking actions by in-depth biomechanical analysis and to apply it to the development and testing of a user-centred sport device.

The cumulative dissertation comprises five papers. The first two include applications of two literature-based (sequential action and proximal-to-distal movement sequences) and two newly developed (balance and stability indicators and initiation action identification) models. Based on the outcomes, Paper 3 comprises additional novel models for performance indication, called leg and femur vector spreading angles (VSA), which allow to differentiate between skill levels of athletes with high accuracy and are strongly related to general hip joint flexibility. The final two papers focus on the development and testing of a sport device for targeted training of hip joint flexibility and strength, to ultimately improve kicking performance. The device, named "Flexibility Trainer" was designed, manufactured, and patented within the EU.

The studies showed significant correlations or group differences between sequential duration, the balance and stability models, and range-of-motion at various phases and nodes during the technique execution (particularly before and during the first kicking movement), as well as at static flexibility.

The device was examined using general and sport specific pre- and post-exercise tests, before and after a training protocol consisting of three exercises with three repetitions each. Results show significant improvements of static flexibility and sport-specific ROM. Therefore, the device is believed to allow for a new level of efficiency in training by simultaneously increasing general and sport specific flexibility by a higher rate than found in previous studies.

XI. Declaration of Authorship

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award (except in the course of the cotutelle agreement); the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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