Bone remodelling during conditioning practice in Taekwon-do

1. Introduction

Conditioning is a central exercise of power in Taekwon-do. The main purpose of conditioning is the strengthening, or toughening, of the bones and surrounding tissue to withstand the impact of attacking and defining techniques in Taekwon-do. Three core body parts that require conditioning are the hands, forearms and feet. In each of these extremities, different bones, joints and ligaments need strengthening, depending on the application of a technique that is learned by the student.

The Taekwon-do encyclopaedia provides guidance on tools for conditioning (like forging pads) and how to apply attacking and defending onto those tools, but does not specifically teach best practice for frequency and strength. Conditioning might be thus taught slightly differently in different Taekwon-do schools and during national black-belt seminars, but the core principles are well established and shared between instructors in ITF Taekwon-do. During the early stages of training, the students conditions their fists by push-up on the knuckles and their forearms (or knifehands) by 'forearm-to-forearm' (knifehand-to-knifehand) blocks with opponents or during three-step sparring. Somewhat later, the students are required to condition the extremities themselves, in particular the fists (e.g., forefist or backfist). Best practice as taught to me during black-belt seminars in the UK is regular punching of a conditioning pad, ten to thirty times a day. Conditioning needs to be performed for at least 3 months to have any real effect.

Conditioning, like all other training practices in Taekwon-do, is informed by years of practice and experience by General Choi and (Grand) Masters around the world. Nonetheless, how bones adapt to a conditioning regime can also be viewed from a perspective of human physiology, and training methods could be informed by knowledge obtained in the medical sciences. Strengthening of bones has been experimentally studied well before the birth of Taekwon-do and a lot is known on how bones adapts to conditioning. In this thesis, I will summarise current scientific knowledge that could help to inform Taekwon-do on conditioning practices. The majority of recent research relevant to conditioning was performed in a single lab, that of Prof. Dr. Charles H. Turner (1961-2010) from Indiana University Purdue, USA, who has published over 250 papers on this topic. By necessity, rather than choice, the majority of this thesis is thus based on the hypotheses and findings from this single group of researchers.

Although scientific knowledge forms the core of this thesis, where possible I have placed knowledge in the context of conditioning practices in Taekwon-do. To enhance reading experience, I have used conditioning of the forefist (front punch) as the main example throughout, as in my experience the front punch is often considered a key challenge by the Taekwon-do student, including myself. This does not imply that conditioning of other techniques is less critical and examples discussed throughout this thesis will equally apply to the conditioning of techniques other than the front punch.

I note here that in Taekwon-do 'mass' and 'speed' are two of the six principles of the *theory of power*. In the discipline of physics, 'power' is defined the rate of doing work or, in other words, the amount of energy transfer per unit of time. From a scientific perspective, the word 'power' is thus not the most useful description as the actual time during which a attacking tool hits a target is very short and transient. Similarly, 'force' is defined as the ability of one object to change the motion of a second object and is given by the mass multiplied by acceleration (or deceleration). When Taekwon-do student hits a target, the fist will decelerate very quickly to zero speed, so it follows that 'force' is dependent on the speed of the fist at impact and the mass behind the impact, as described in the theory of power. From this somewhat confusing and difficult to follow description it is clear that 'force' is still not the best description to describe energy transfer from the attacking fist to the target. In my opinion, the term ‘**impact**’ in mechanics (also known as impulse) is a more convenient description to describe the transfer of energy. ‘Impact’ is described as the high ‘force’ applied when two objects collide and is given by the mass multiplied by speed (of the attacking tool, assuming the receiving target is stationary). Throughout this thesis I will use the word ‘impact’ or ‘impact force’, rather than ‘power’ or ‘force’.

Somewhat confusingly, in biomechanics, the effect of conditioning is studied by applying a force on a bone for a set period of time. However, rather than call this ‘force’, the field of biomechanics tends to call this ‘**loading**’. I will retain the use of the word ‘**loading**’ and ‘**load**’ in this thesis when referring to scientific experimentation. Please note that when using the concept ‘loading’ or ‘load’, the time period needs to be given for which this load is applied. The load multiplied by time then has the same physical meaning as impact or impulse.

2. Mechanotransduction

Mechanotransduction is the term used to describe how conditioning of the front punch will lead to signals that, ultimately, will have a physiological effect on the bones. In other words, the process of mechanotransduction describes how (repeated) impact of the front fist on a conditioning pad (or board/brick) will lead to signals in the body that eventually result in the strengthening of bones. Section 2.2 will provide a basic overview of how conditioning leads to signals in the bone. Section 2.3 will then continue the discussion on how bones are strengthened after the signals are generated. Before these processes can be explained, the structure of bone needs to be introduced and this is done in Section 2.1.

2.1 Bone structure

The main strength of any bone is due to the cortical bone, also known as compact bone. The cortical bone is the denser material of the bone that surrounds the hollow or softer inside of the bone. As such, bone adaption or strengthening is mainly performed by alterations in the cortical bone. Cortical bone is a composition of organic material (mainly collagen) and inorganic minerals (primarily hydroxyapatite which is a salt of calcium and phosphate). Collagen and hydroxyapatite are unable to generate or transduce signals as these are ‘non-living’ materials (i.e., they are not cells). Mechanotransduction is instead performed by living cells that are associated with the cortical bone, i.e. located at the surfaces of the cortical bone material. Human (and all mammal) bones have four different surfaces (or envelopes), depending on the location: the periosteal, endocortical, trabecular and intracortical envelopes (see Figure 1).

GLOSSARY

Basic multicellular units (BMU): temporary anatomic units of osteoclast and osteoblast where old bone is resorbed and new bone is made.

Compact bone: See cortical bone.

Cortical bone: The dense material of the bone that surrounds and protects the hollow or softer inside of the bone.

Endocortical envelope: the inner surface of cortical bone (the surface of cortical bone on the inside of the hollow bone).

Force (in Physics): the ability of one object to change the motion of a second object. Force is given by the mass multiplied by acceleration (or deceleration) and has the units Newtons (N).

Harversian canals: microscopic tubes in the cortical bone that allow blood vessels and nerves to travel through them.

Impact (in mechanics): the transfer of kinetic energy when two objects collide (or high force applied to one object by collision with a second object). Impact is given by the mass multiplied by speed and has the units Newton seconds (N s).

Impulse (in mechanics): another word for impact.

Intracortical envelopes: The surfaces associated with small hollow tubes (Harversian canals) that transverse cortical bones.

Load or Loading (in mechanics): Applied force, but the preferred term in biomechanics.

Mechanotransduction: The process by which loading on a bone results to signals in the body that ultimately result in bone adaptation.

Osteoblast: A bone cell which secretes bone material, thereby forming new bone during bone modelling and remodelling.

Osteoclast: A bone cell that resorbs bone material as part of the bone remodelling.

Osteon: the fundamental functional unit of cortical bone. Osteons are roughly cylindrical structures that traverse the bone. They are several millimeters long and around 0.2mm in diameter.

Osteoprogenitor: one of the cells in the inner layer of the periosteal envelope that develop into osteoblasts

Periosteal envelope: the outer surface of a bone (the outside surface of cortical bone).

Power (in Physics): the rate of doing work or, in other words, the amount of energy transfer per unit of time.

Trabecular envelope: Surfaces in cancellous bone. Cancellous bone is porous and hence in the pores are surfaces.

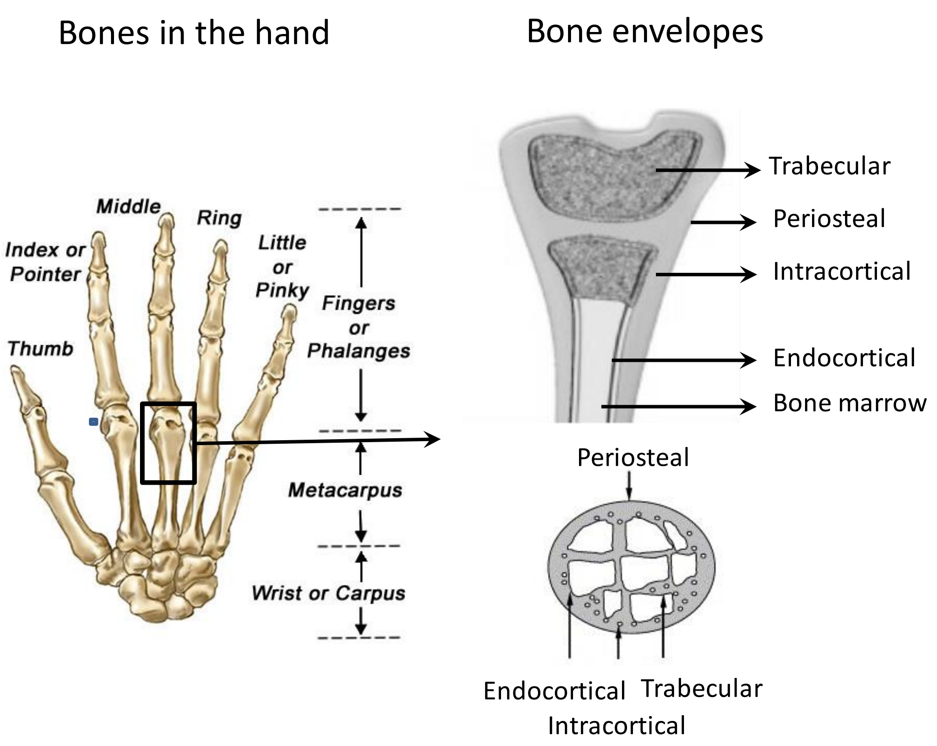

Figure 1: **Schematic presentation of bone structure and its envelopes**. The periosteum is the very outside of a bone where the periosteal envelope is found. The trabecular surfaces are found in the spongy material known as cancellous bone found in parts of the bone centre. It is a porous material in which cells reside, mostly red bone marrow. The surface between the hollow inside and the cortical bone is known as the endocortical surface. Finally, the cortical material itself contains many small channels along the long axis of the bone, known as Harversian canals. The surface that lines the Harversian canals is known as the intracortical surface.

Inside the cortical bones are microchannels that house blood vessels and nerves. These microchannels are known as Harversian canals and are very important in bone maintenance (see sections below) and forms the centre of tubular structures known as osteons (see Figure 2, left). Around the canals, a lamellar structure is formed that contains cells imbedded in the cortical bone. These cells are known as osteocytes and are connected by even thinner microchannels that are filled with fluid (canaliculi; see Figure 2, right).

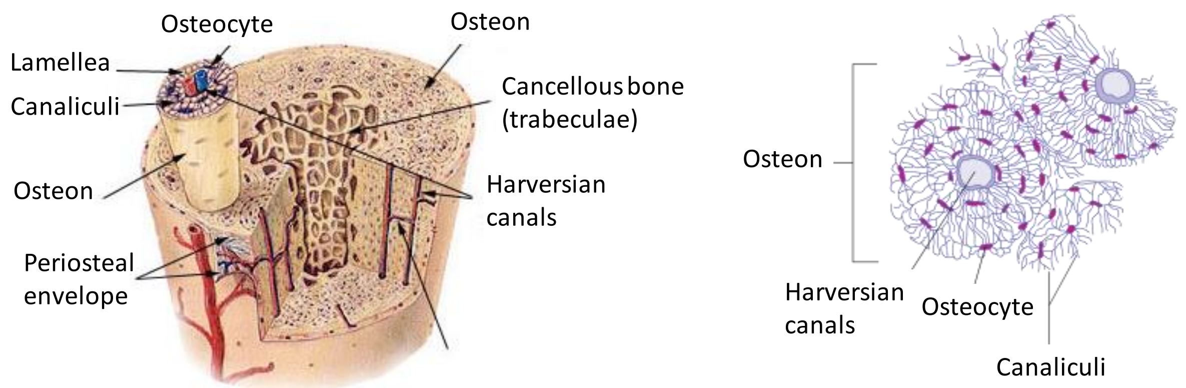

Figure 2: **Schematic presentation of osteon in the cortical bone.**

2.2 Sensing mechanical loading

How mechanical loading is sensed by the bone has only started to become clear in the last decade. Mechanical sensing is performed by the cells that are imbedded in the bone (Chen et al., 2010, Huang and Ogawa, 2010). Two cell types have so far been identified as 'mechanosensing': osteocytes and osteoprogenitors.

Osteocytes are the cells embedded in the cortical bone, for instance around the Harvesian canals (Figure 2). The key role of osteocytes was elegantly shown in 2007 and 2008, when mouse models in which the osteocytes were genetically removed or made to malfunction were unable to respond to mechanical stimuli and as a result developed fragile bones. Osteocytes are surrounded by a network of canaliculi that are filled with fluid. Current thinking focusses on the idea that mechanical loading on the bone leads to small deformations of the bone, narrowing and widening some of the canaliculi and inducing fluid flow through the channels. Shear forces due to fluid flow (shear is the strain produced when two layers are laterally moved with respect to each other) is detected by the osteocytes which lie at the centre of the canaliculi networks.

Experimentally studying the mechanical effects on osteocytes is difficult. The central dogma in science is that effects can be experimentally proven by isolating the system and comparing responses with and without a stimuli. This, however, provides a difficult conundrum for science. By isolating the osteocytes, they are necessarily dissociated from the canaliculi. Furthermore, cells in general are known to respond strongly to their direct environment and by isolating osteocytes, removing them from the bone, one necessarily changes their environment. Finally, it is not possible to accurately mimic the mechanical forces that are sensed in the bone by the osteocytes. One can hardly slam a Petri dish of osteocytes into a breaking board. In spite of the difficulty, it is clearly shown by many experiments that mechanical forces induce large responses from osteocytes. Osteocytes that are mechanically stimulated release several chemicals that can stimulate processes in their direct environment (i.e. signal *transduction*). Mechanical forces are also thought to trigger a self-destruction mechanism in the osteocyte cell, known as programmed cell death or apoptosis, which, in a second process, releases chemical signals to its direct surrounding. The details of the molecular signals are still being studied and debated, but it is clear that these signals influence other cells which are responsible for bone adaptation (see section 2.2).

The second cell type that has recently been identified to be involved in mechanosensing is osteoprogenitors. Osteoprogenitors are cells formed in bone marrow and are destined to become osteoblast cells. The transformation of one cell type to another is known as differentiation. Osteoblast are responsible for forming new bone material (see next section) and thus controlling differentiation of osteoprogenitors into osteoblast will directly impact bone adaptation. How osteoprogenitors are involved in mechanosensing is much less clear compared to the osteocytes. Conflicting experimental data indicate that this aspect is not yet fully understood (Chen et al., 2010). Current thinking is that osteoprogenitors sense fluid flow after mechanical deformation of the bone. However, osteoprogenitors also sense their direct environment which holds information on where in the bone an osteoprogenitor cell is located. Based on a combination of signals, differentiation to osteoblast could be triggered, but this is difficult to reproduce in a laboratory setting.

2.3 Bone repair and remodelling

Even when mechanical demand or loading on our bones is constant over prolonged periods of time, bone material will constantly weaken as consistent use will lead to bone fatigue. Fatigue in materials is a universal property and in engineering fatigue limits the lifespan of buildings and other structures. However, unlike in engineering, bones are constantly repaired as the body continually replaces old bone with new bone material. This is known as bone remodelling and differentiates itself from bone modelling, which is the term used to describe bone formation in the growing infant.

After mechanical deformation of the bone is sensed by osteocytes and osteoprogenitors, the bone structure is adapted during remodelling. A fundamental and key aspect of bone adaption is that bone is only strengthened at places where mechanical deformation has been sensed. A bone will deform most at the position where it is weakest (with respect to the load that is applied). As a result, the body will only strengthen a bone at its weakest position rather than the whole bone. This is known as Wolff's law, after work by Julius Wolff and Wilhem Roux in the 19th century that showed that bone is specifically strengthened to meet mechanical demand.

Bone adaptation does not only involve strengthening. When a Taekwon-do students stops conditioning, bone material (and strength) is ultimately lost again. A very illustrative example of the latter is observed in spaceflight, where astronauts are confronted with bone loss as mechanical forces are much weaker in the absence of gravity.

Like mechanotransduction, bone remodelling is performed by living cells at the four envelopes (or surfaces) of the bone (see section 2.1 and Figure 1). Bone remodelling is performed by two cell types: osteoblasts and osteoclasts. Osteoclast are cells that resorb bone and osteoblast form new bone. The activity of osteoclast and osteoblast is highly orchestrated and the balance between the activities of the two cells will dictate whether bone is lost or whether more bone material is made (i.e., bone strengthening). Bone is remodelled at the basic multicellular units (BMU), which are temporary anatomic units of osteoclast and osteoblast where old bone is resorbed in new bone is made. BMUs in the cortical bone traverse the bone in a nearly longitudinal orientation. At the 'head' of the BMU, osteoclast resorb the bone, followed by osteoblast that form new bone. As the BMU traverses through the bone, a central cavity is kept open (i.e. where bone is not reformed by the osteoblast) and this cavity forms the Haversian canal mentioned in section 2.1. Some of the osteoblast are embedded in the bone material as it is formed. These osteoblast change into (differentiate into) osteocytes. This process does not only occur inside cortical bone, but also at the periosteal and endocortical envelopes. Intracortical bone remodelling cannot strengthen a bone as there is no additional space to deposited more bone material. As such intracortical bone remodelling is mostly a maintenance and repair process. Additional bone resorption and deposition is, however, possible at the periosteal and endocortical envelopes and it is at these surfaces where the majority of bone loss or deposition is observed during bone adaption (see Figure 3, top right).

Imagine a Taekwon-do student conditioning the front fist. Two metacarpal bones (Figure 1) will experience bone compression, which will already result in bone adaption. However, if weak, the metacarpus bones (Figure 1) might bend under the impact of the punch. The direction of bending will depend on the weakest parts of the bone, where 'weakest' has to be understood in relation to the front punch. Assume the bone slightly bends upwards when seen from the top of the fist. In this case, the top of the metacarpus bone will sense a 'pulling apart' loading (known as tension) and this will be the part of the bone that is deformed most. Mechanotransduction will thus be highest in this area and new bone will be formed on the periosteal surfaces on that side of the bone. By only strengthening the bones at their weakest point, nature has evolved a way to adapt bones to particular mechanical loads with minimal increase in bone weight. This process is clearly shown in an experiment where the main result is summarised in Figure 3. The forelimb (forearm) of a rat is repeatedly (intermittently) subjected to compressing forces for a period of 16 weeks. After this period, the bone material is only increased by 7%, but by specifically forming the bone at the side where the bone is bend, the bone strength (to compression!) is improved by 64%.

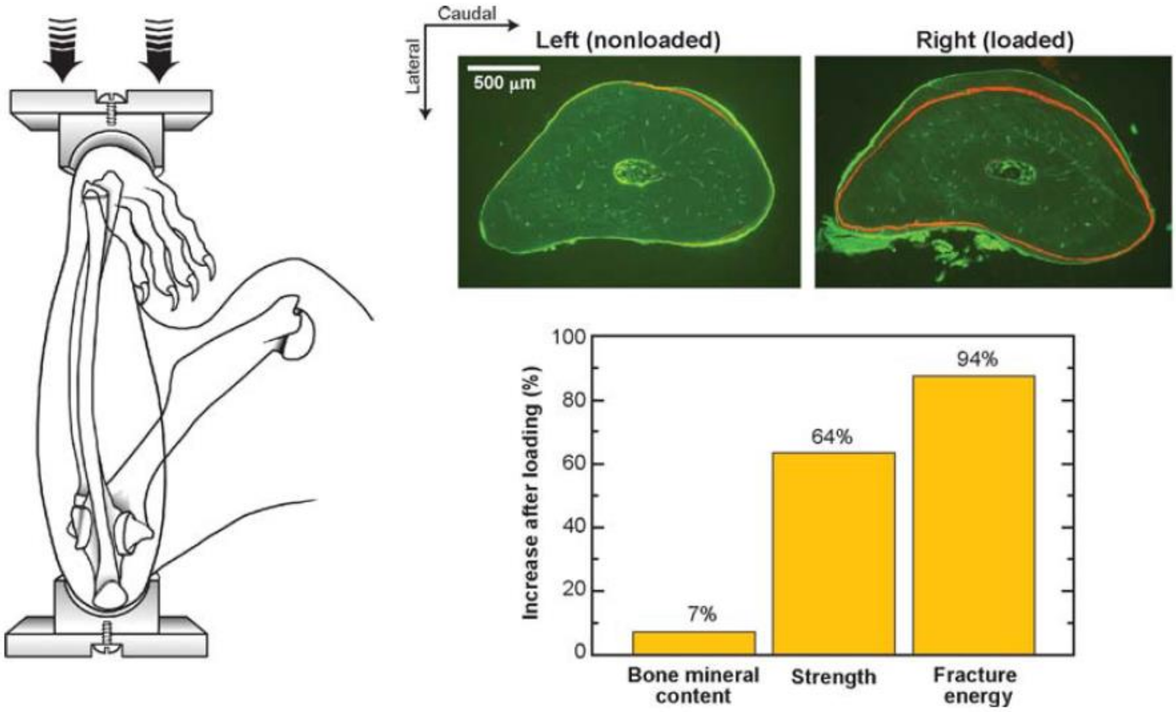

Figure 3: Bone adaption of a rat ulna (forelimb) after loading using the apparatus schematically shown in the left. Loading was applied for 3 min/day, 3 days/week for 16 weeks. Top figure shows a cross section of the ulna where is clear that bone adaption increases the lateral bone of the ulna. The bar plot at the bottom indicates the increase in bone mineral content, strength and energy required to fracture the bone when rat with and without conditioning (i.e. loaded and non-loaded) are compared. Figure taken from (Robling et al., 2002).

3. Rules that govern bone adaptation

The rat's forelimb in Figure 3 was not subjected to a continuous (or static) force as a continuous force has been shown to have little effect on bone adaptation (Robling et al., 2006). Instead, bone strength improvements are shown to be greatest when loading is separated into short bouts (Robling et al., 2006, Robling et al., 2002). The rat's forelimb in Figure 3 was subjected to force for only 3 minutes per day and only 3 days per week. What regime is most beneficial for bone adaption has extensively been studied in rodents (Robling et al., 2006). As process of bone remodelling is the same among mammalians, it is generally assumed that the rules for bone adaptation experimentally observed for rodents also applies to humans and should thus apply to the Taekwon-do student conditioning. In this section, the rules that govern bone adaption while conditioning will be summarised.

Dynamic conditioning: Already in 1971, it was shown that dynamic forces, but not static ones, induced bone adaptation. Both the frequency and the magnitude of the force determines how much the bone adapts. Importantly, bone adaptation seems to improve linearly with frequency. In an experiment, the right tibiae (lower leg) of a rat was loaded for 36 cycles a day for 2 weeks. At 0.1 Hz (i.e., one cycle every 10 seconds), almost no bone adaptations was observed. At 0.2 Hz, bone adaptations increased about 2 fold, at 0.5 Hz this was 4 fold and so on (Turner et al., 1994). Bone adaption improved up to frequencies of 50 Hz, which was the highest frequency studied by Turner et al. (1994). However, other studies show somewhat contradicting results for frequencies above 10 Hz, where some studies suggests improvements up to 90 Hz, while other indicate an optimum frequency between 5 – 10 Hz. In spite of the contradicting results, it seems clear that for the Taekwon-do student, punching the conditioning pad faster (without compromising on impact), rather than longer, will be most effective. Punching much faster than 2 Hz (i.e. twice per second) without losing impact will be a challenge for any Taekwon-do student, thus in practice the student should try to condition using as fast as convenient punching rate. Importantly, these experimental studies show that increasing the frequency can offset the loading (and thus likely impact) that is needed to induce bone adaption. Fast punching with less impact might possibly outweigh slow punches with more impact. The experimental studies were done on rodents (i.e. loading the rodents' tibiae or ulnae) and it is not straightforward to convert loading (at a particular frequency) of these studies to a suggested impact force for conditioning the forefist of a Taekwon-do student. Thus, although these studies can advise on frequency, they are less informative on impact force the student would have to use.

Daily duration of conditioning: In this subsection, 'duration' is meant as the time a student takes to condition his fist each day. In experimental studies it has been shown that increasing the number of loading cycles each day does not continue to improve bone remodelling. These studies show that as the number of cycles of loading is increased more and more, the influence on bone adaption starts to diminish. Based on these rat studies, it seems that conditioning has little added benefit above 40 cycles a days (Burr et al., 2002). This coincides with the taught conditioning training in Taekwon-do, which advises 10-30 punches on a conditioning pad per day.

Long-term conditioning regime: Besides the frequency (and impact) and number of punches on the conditioning pad each day, conditioning can be measured with respect to how long the student has been conditioning for (i.e., how many days, weeks or months). Furthermore, it can be considered that the student does not condition every day, but perhaps twice or three times a week. Furthermore, the student might not condition every week, but s/he might have breaks of one or more weeks in which the student does not condition. As is clear, there are an infinite number of parameters that can be considered, many of which will not have been experimental studied. Nonetheless, two experimental studies give interesting insights and show that conditioning does not have be performed every week.

In the first study, the loading was either increased or decreased in periods of 5 weeks (e.g. after each period of 5 weeks, the force was increased or decreased). Counterintuitively, it was observed that the rat with progressive *decreasing* loading showed a *larger* amount of bone adaptation (Robling et al., 2006). I.e., starting with the most impact and then reducing the impact over time seems beneficial for a Taekwon-do student that is conditioning. In a similar study with rodents, it was found that bone adaptation improves if conditioning regimes include 'time off' or rest periods. For instance, bone adaptation was higher when forces were applied in a 5 weeks periods in an ON-OFF-ON pattern compared to a ON-ON-ON (i.e. constant) patterns.(Saxon et al., 2005) How long rest periods have to be to most effective is not fully established, but results suggest that rest period and active periods have to be somewhere between 2 and 10 weeks. In summary, these studies suggest that a Taekwon-do students takes rest periods of several weeks between periods in which the pad is punched with maximal impact (although the latter remains difficult to define).

Impact force during conditioning: The final parameter that clearly needs to be considered for conditioning is impact. It is clear that if extremely small impact forces are used, no bone adaption will result. However, when applied impact forces are too large, this will result in overuse and microdamage, ultimately leading to fractures (i.e., breaking bones). As mentioned earlier, even under normal use, bones are constantly damaged due to fatigue and bones are constantly remodelled to stop this leading to fractures. However, during overuse, remodelling cannot keep up with microdamage accumulating and prolonged periods of overuse thus leads to full fractures as the bone strength reduces. Overuse and exercise-induced bone injuries do not only occur in Taekwon-do and other martial arts, but are common among all athletes with repetitive forces, including, for instance, long distance runners.

The type of microdamage depends on how the loading is applied (mode of loading). Two major modes of loading are compression and tension. Compression is the loading along the length of a bone. Thus, a forefist punch results in compression to the metacarpus bones in the hand (Figure 1). Tension is the opposite to compression and with respect to Taekwon-do is typically formed on the side of bone if the impact comes from the side. Thus, blocking with the outer forarm impacts the ulna, which leads to tension forces on the inner forearm side of the ulna as the bone slightly bends under the force.

Microdamage under compression results in linear microcracks that generally run oblique to the direction of force. With overuse, these microcracks can lead to microfractures. A potent example of possible overuse occurred at the school at which I train. A student of about 40 years old, who was well conditioned and has broken bricks regularly with a front punch, broke his metacarpus in class after punching a relatively 'easy' breaking board. X-ray photos showed the metacarpus was broken obliquely just behind the knuckle (Figure 4).

Figure 4: Fracture in metacarpus (in red circle) of an experienced Taekwon-do student after punching a breaking board.

Overuse can have consequences many weeks to months after conditioning. Upon conditioning, mechanosensing and microdamage induces the bone to be remodelled *via* a BMU process (see section 2.3). BMUs in the intracortical bone leads to temporary increase in porosity as the osteoclast resorb bone in the osteons. During this period of repair and remodelling, the bone is more fragile. In experiments with dogs, it was shown that new remodelling BMUs have 4 to 6 times more fatigue induced microcracks. In other words, the remodelling process during a regime of conditioning can play a significant role in the formation of fractures. While conditioning, a Taekwon-do student will pass through a period of reduced bone strength, increasing the potential of a full fraction if performing a front punch of a ‘real’ target like a breaking board or brick.

Microdamage with age and gender. Finally, bone remodelling is known to differ strongly with age and gender (Schaffler et al., 1995). Microdamage has been shown to increase exponentially with age and increases more quickly in women than in men. The exponential dependency means that for every 10 years, microdamage increases at least 2 fold for men and 3 fold for women, but between the ages of 20 and 40 years, this difference is 4 fold and 9 fold for men and women, respectively (Figure 5). Although differences in physique between students is large and one has to be careful not to generalise, students who start Taekwon-do at a more mature age might need to take extra care with conditioning.

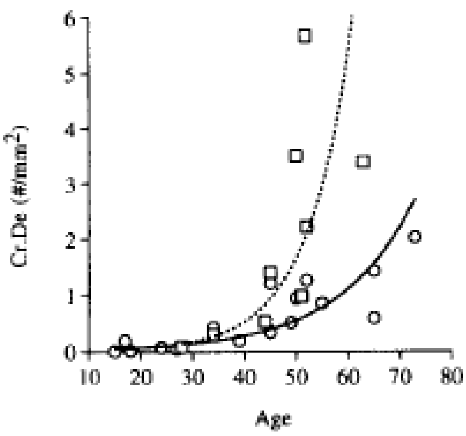

Figure 5: The number of microdamage (in number per surface area) as a function of age for men (solid line) and females (dashed line) of normal participants (i.e., not Taekwon-do students nor athletes of other sports). Image taken from (Schaffler et al., 1995).

Currently, females in UKTA are not required to condition their fists nor are they required to break a brick with a hand technique at gradings. The latter is sometimes justified on aesthetic reasons, as conditioning can have a significant effect on the shape of the hand, in particular the knuckles. However, perhaps more important in this respect is the fact that bones of females above the age of 30 or 40 are on average more likely to contain more microdamage and thus more likely to develop fractures during conditioning.

Conclusion

Based on scientific studies, conditioning is best performed by punching a conditioning pad 20 to 40 times a day for 3 to 4 days a week. Rest period of several weeks are recommended. Experimental studies are typically limited in timespan as rodents only live for 1-2 years, while time-is-money in research. Thus, based on experimental studies on rodents, it is not possible to make recommendation on how long a student needs to condition before starting to break boards and ultimately bricks. However, a period of at least 3 months is recommended based on scientific experimentation and experience from Taekwon-do. During conditioning training, bones can temporary decrease in strength and the risk of fractures can increase. Based on this data, I would recommend students to stop conditioning 4-5 weeks before they attempt a major break for the first time (e.g. a brick with a front punch). Finally, although women are not required to condition their hands, they would be more prone to bone damage if breaking at an older age (> 40 years old).

Personal reflections

I am professor in molecular biophysics and my day-to-day research has in no way any relevance to the topic of this thesis. Nonetheless, my affiliation is with the School of Biomedical Science at the University of Leeds, where we educate over 100 students a year in Medical Science. This environment naturally enhanced my curiosity on conditioning training as recommended in Taekwon-do and how this training is reflected by experimental knowledge in science. During my studies into the background of this thesis, I was very comforted by the fact that recommendations made by my seniors and instructor indeed closely align to the knowledge on bone adaptation and remodelling. Whether by science or experience, Taekwon-do provides effective advice to their students for bone strengthening. The only surprising finding I encountered was that rest period of several weeks can be beneficial to bone adaptation. However, I expect that many students already implement 'rest' period, even if this is not by design.

Throughout this thesis, I have used front punch as the typical example for conditioning and breaking. This was chosen in part due to my personal experience. Although I have broken bricks in class with hand techniques, I am still ashamed that I have not completed a break with a hand technique during my gradings for I, II nor III degree. This is in part due to the fact that my hands are fundamental to practicing my profession and a major fracture to one of the bones could have significant influence on my career. I have thus always followed a very conservative conditioning regime and, with respect to power, have not satisfactory performed during gradings. I hope that my knowledge obtained while writing this thesis will help me in future conditioning.

Finally, I have found two relevant studies into conditioning in martial arts (Shin et al., 2011, Vit et al., 2015). However, neither of these two studies are performed to a standard I would expect for a high-impact observational or experimental study and hence I have not used these studies for my thesis.

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