Theme 1. Physics principles of specification and quantification of musculoskeletal structures motor function and human body tissues mechanical properties

Problem
Human musculoskeletal structures and tissues conditions definitive diagnostic test

Attendance prerequisite checklist. Note! Answer in writing to perform

Define or explain physics basics listed below

1. A force in Mechanics is referred to as ______________________________________.

2. The major kinds of forces in Mechanics are referred to as ______________ (definition) ______________ (formula); ______________ (definition) ______________ (formula); ______________ (definition) ______________ (formula); ______________ (definition) ______________ (formula);

3. Newton's laws state that
the first law: ____;
the second law: ____;
the third law: ____.

4. A mechanical work done under an object may cause changes of an object ____________, ____________, ____________, ____________.

5. An energy in Mechanics is referred to as of two types ____________ and ____________.

6. The principle of total energy conservation is referred to as ____.

7. The principle of moments and the resolution of forces is referred to as ____.

8. An object deformation is referred to as ______________________________________.

9. The main types of deformation are ___________________, ___________________, ________________, and deformations as combinations of these are ______________ and ___________.

10. A stress in Mechanics is defined as ________________________ and a strain is defined as __________________.

Information resources

1. http://djelatnici.unizd.hr/~mdzela/nastava/Physics.pdf

2. http://ruina.tam.cornell.edu/Book/RuinaPratap8-21-10.pdf

Introduction

Lever action of muscles and bones. Torques. Skeletal muscle contraction maintains posture and produces movement of the bones of the skeleton. In all cases the type of the movement of the bones is rotation. Therefore, it is possible to estimate the movement of the bones on the base of the laws of the rotation.

Suppose an object is subjected to two equal but opposite forces. The net force is zero. So, the object is in translational equilibrium. Nevertheless, it may not be in rotational equilibrium. In addition of **F** = 0 we require another equilibrium condition to exclude the possibility of rotational motion.

The quantity that indicates the ability of the force to cause rotation is called **torque**.

The rigid body is in rotational equilibrium when there is no net torque acting on it.

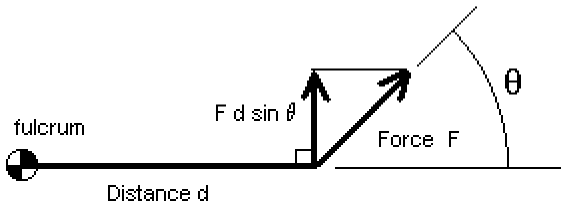

Figure 1

The torque **τ** depends on the force **F**, the distance **r** from a point of the axis of rotation to the point where the acts on the object, and the angle **θ** between the distance **d** and force **F**. The magnitude of the torque about fulcrum is $\tau = d \cdot F \cdot \sin\theta$ (fig. 1)

The dimensions of a torque are force time length so the S.I torque unit is (Newton·meter). The direction of **τ** is given by the right-hand rule and indicates the axis about which rotation will tend to occur. To illustrate the right-hand rule suppose **r** is in + x direction and **F** is in + y direction. Using the right-hand rule, we point the fingers of our right hand in the + x direction.

When our palm faces the + y direction, and our thumb is out of the pages, we can rotate our fingers 90^0 toward the + y direction. Thus **τ** is out of the page.

Equilibrium of the rigid bodies. A pair of forces with equal magnitudes but opposite directions acting along different lines of action is called a **couple**. The pair of forces applied to the body do not exert a net torque. There are **two conditions for the equilibrium of a rigid body:**

- the net force on the object must be zero;

- the net torque on the object computed about any convenient point must be zero.

These two conditions ensure that a rigid body will be both translational and rotational equilibrium.

Levers: mechanical advantage. A liver in its simplest form is a rigid bar used with a fulcrum. A liver is example of machines. In this case a force $\mathbf{F_a}$ is applied and load force $\mathbf{F_L}$ is balanced (fig. 2). The mechanical advantage (M. A.) of the machine is defined as a ratio of the magnitudes of these forces: M.A. = F_L/F_a. When the forces are perpendicular to a lever, its mechanical advantage is M. A. = $F_L/F_a = x_a/x_L$.

Many examples of levers are found in the bodies of animals (fig. 2). Muscles provide the forces for using these levers. Three classes of levers (I, II and III) are defined according to the relative position of $\mathbf{F_a}$, $\mathbf{F_L}$ and the fulcrum.

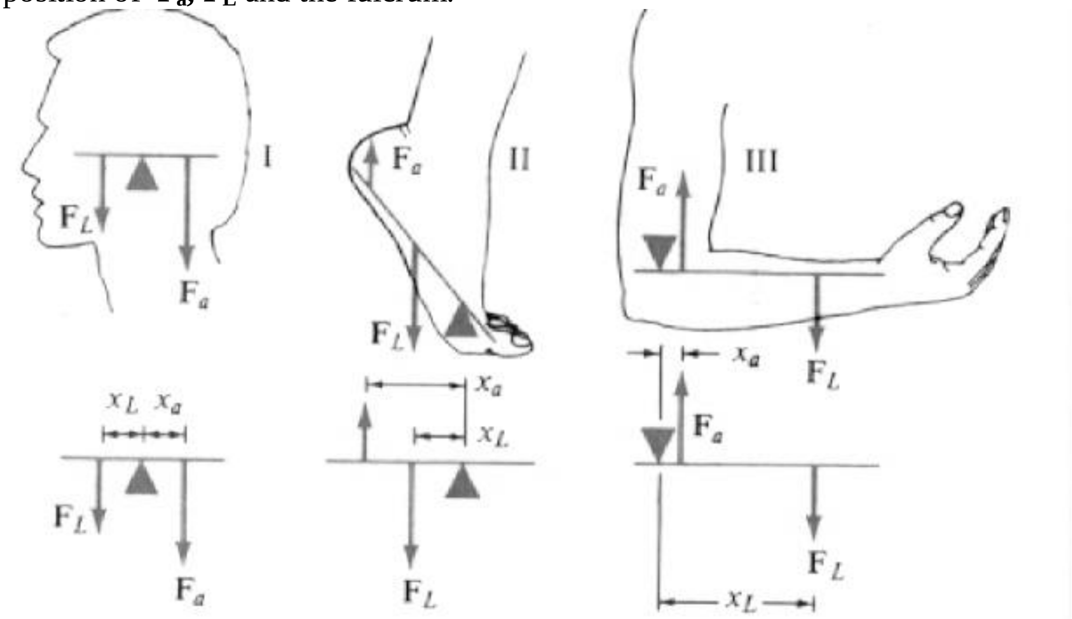

Figure 2

General aspects of stress and strain. An object made from any real material will always be deformed at least slightly and may even break when forces or torques are applied.

Although materials are held together by complicated electric and magnetic forces among the molecules, the effects of these forces can be categorized quite adequately using a few measured quantities.

The deformations of materials are determined by the force per unit area, and not by the total force. Because of this it is useful to define **the stress in the bar of cross-sectional area A subjected to a force F as the ratio of the force to the area $\sigma = F/A$.** The stress is opposed by the intermolecular forces within the material.

Three kinds of stress are commonly defined.

Tension stress is the force per unit area producing elongation of an object.

Compression stress acts to compress an object

Shear stress corresponds to the application of scissor like forces.

The change in the length of the bar under tension or compression stress is proportional to its length. The strain ε is the fractional change in length $\varepsilon = \Delta l/l$.

There are three kinds of strains: tension, compression, and shear. Any deformation of an object can be considered as a combination of these three strains.

The relation between the stress and the strain for a material under tension can be found experimentally. Typical results are shown in figure 3.

The elastic deformations of a solid are related to associated stresses by quantities called elastic moduli. In the linear region of the stress-strain graph for tension or compression, the slope equals the stress-to-strain ratio and is called the **Young's modulus E** of the material: $E = \sigma / \varepsilon$.

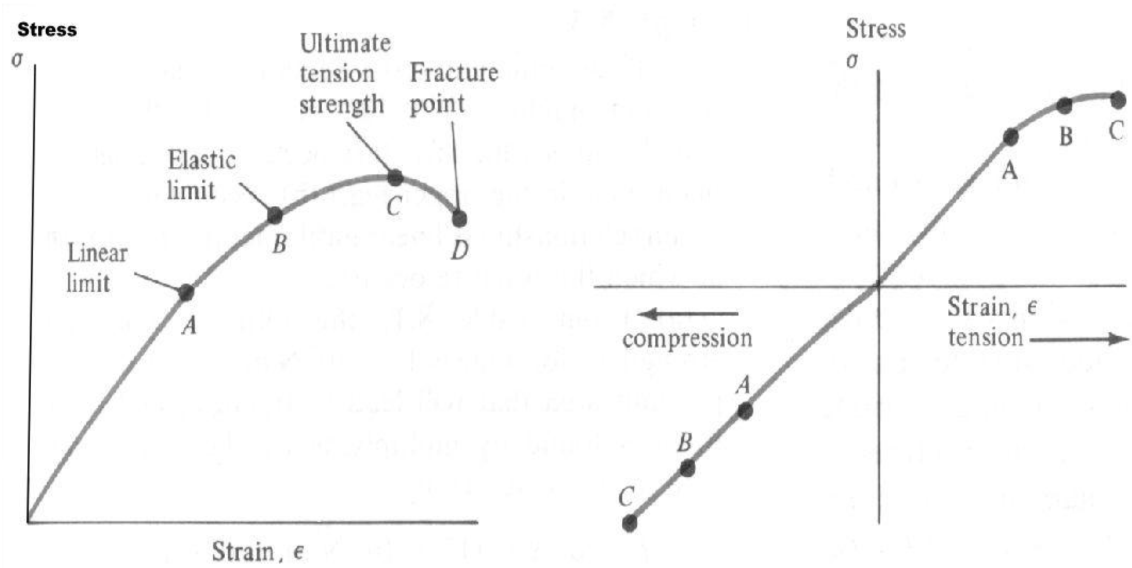

Figure 3

For inhomogeneous materials such as bone, the moduli for compression and tension are different. The linear stress-strain region is also called the **Hooke law region.** In this region, since the stress is linearly related to the strain, the force is linearly related to the elongation. This can be seen using the definition of Young modulus rewritten as $\sigma = E\,\varepsilon$. With the definitions of the stress $\sigma = F/A$ and the strain $\varepsilon = \Delta l/l$, this becomes $F/A = E\cdot\Delta l/l$. Thus, in tension or compression the force on an object is proportional to its elongation, $F = k\,\Delta l/l$, where **k** is called the **spring constant**, and $k = EA/l$. Equation $F = k\cdot\Delta l/l$ is called **Hooke law**. As long as an object under stress is in the linear region, Hooke law is valid.

Bending strength. The figure 4 shows a bar of length **l** and rectangular cross-section with sides **a** and **b**. Placed on two supports, it bends somewhat under its own weight. When the bar bends with a radius of curvature **R**, the internal torque **τ** in the bar is given by $\tau = E\cdot I_A / R$, where E is Young's modulus for the material, and I_A is called the **area moment of inertia**. For rectangular bar the area moment of inertia is $I_A = a^3 \cdot b/12$.

Many results suggest that to construct strong, light structural members, most of the material should be located as far as practical from the neutral surface.

Nature has made extensive use of the principle that hollow structures are stiffer than solid ones of the same cross-sectional area. Bones are generally hollow. For example in the human femur the ratio of inner and outer radii is about 0.5 and the cross-sectional area is only 78 percent of that of a solid bone with the same bending strength.

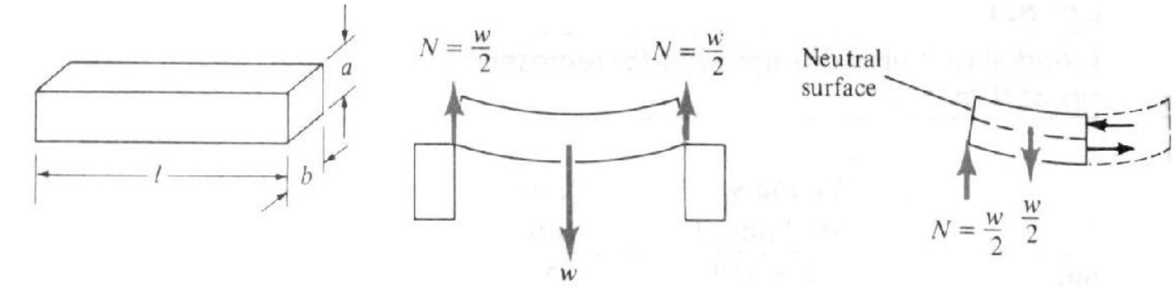

Figure 4

Shearing and twisting torques.

A simple example of shearing stresses and strains is provided by placing a book on a table and exerting equally large forces in opposite directions on its covers. Each page moves slightly relative to the next one, and the shape of the book changes even though its height **h** and width **w** stay nearly the same. In the figure 5 the book is deformed through an angle α. The upper cover moves a distance δ relative to the lower one. The **shear stress** on the upper cover is $\boldsymbol{\delta_s = F/A}$. The **shear strain** is $\boldsymbol{\varepsilon_s = \delta/h = \tan\alpha}$. The ratio of these quantities defines the **shear modulus**, $\boldsymbol{G = \delta_s/\varepsilon_s}$.

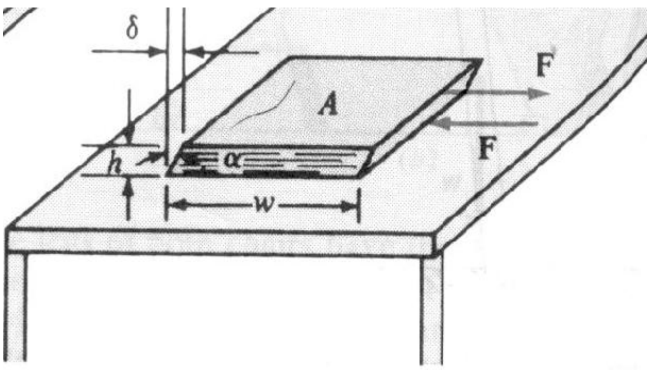

Figure 5

Twisting torques. The figure 6 shows a cylinder fixed at one end. A forces couple is applied at the free end, so that there is a torque directed along the axis. If the resulting deformation is not too large, it is found that a plane drawn along the axis of the cylinder becomes twisted. The angle of twist increases linearly with the distance from the fixed end, so that the radial lines remain straight. Lines originally drawn along the outside of the cylinder parallel to the axis become slightly curved.

To find the relation between the torque τ and the deformation α, it is necessary to compute the stress δ_s at various distances from the cylinder axis. Because adjacent cylindrical layers are subjected to shear forces, the stress δ_s and strain ε_s are related by $\boldsymbol{\delta_s = G \cdot \varepsilon_s}$. The torques on each layer are computed and summed, it is found that if α is expressed in radians, $\boldsymbol{\tau = G \cdot I_p \cdot \alpha / l}$. This is similar in form to the result for bending torques, but $\boldsymbol{I_p}$ is **the polar moment of inertia.** For a cylinder of radius r, $I_p = \pi \cdot r^4/2$ (solid cylinder).

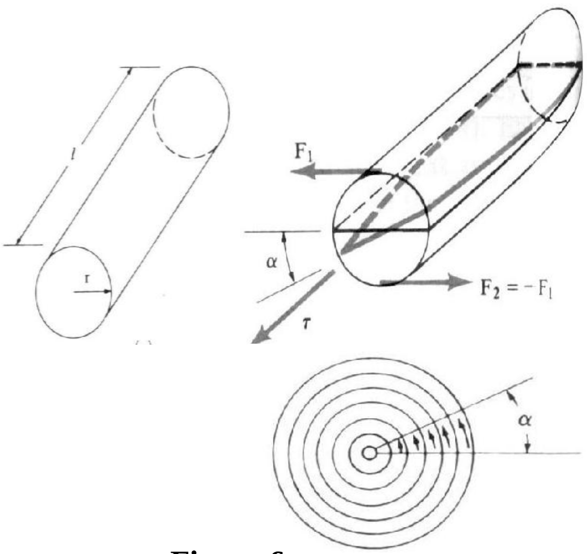

Figure 6

Lab test. Quantification of skeletal muscles contractile function at static and dynamic loading via hand grip and back strength tests to reveal skeletal muscles conditions

Problem
Positive correlation of weight, hand width, height and a body type with hand grip and back strength.

Equipment
Hand grip strength dynamometer ДК-50, back strength dynamometer ДС-200, stopwatch, calculator

Attendance prerequisite
NOTE! Answer in writing to perform

1. Explain the meaning of physics parameter “force”, F. What is its SI measuring unit?
2. Formulate dynamics three principles.
3. Formulate Hooke’s law.
4. Briefly describe skeletal muscle structure and explain how muscle’s fibers are separated into two types. **5.** What are two conditions determining two kinds of skeletal muscle contractions?
6. Consider physical model of a skeletal muscle as an elastic cylinder and reconstruct a formula of skeletal muscle mechanical work done while contracting.

Information resources
1. http://harrycaesar.hubgarden.com/general-test-of-strength-with-dynamometer-grip-devices/
2. https://simonefriedmansls.com/2016/04/ot-tip-of-the-month-hand-strength-and-finger-dexterity/

Introduction

Muscle cell composition. Skeletal muscle is composed of multinucleated skeletal muscle fibers (fig.7). The fibers vary from approximately 10-100 μm in diameter and can be several centimeters in length. The skeletal muscle fibers are grouped into fascicles of approximately 20 fibers by the **perimysium**, a connective tissue sheath that is continuous with the connective tissue surrounding the entire muscle. The perimysium is continuous with the **endomysium**, surrounding each muscle fiber. The endomysium is continuous with the **sarcolemma**, a sheath that contains glycoprotein and closely envelops the true cell membrane of the muscle fiber.

The tight connection between the cell membranes and surrounding connective tissue structures enables the force developed by the muscle fibers to be transmitted effectively to the tendons.

The individual skeletal muscle fibers are divided into **myofibrils** by a tubular network called **sarcoplasmic reticulum (SR)**. The myofibrils are approximately 1μm in diameter and extend from one end of the muscle fiber to the other.

The myofibrils are divided into functional units, or **sarcomeres**, by a transverse sheet of α-actinin protein called the **Z line**.

The myofibrils contain **thick and thin filaments** composed of contractile proteins. **Thick filaments** contain the protein **myosin** and are approximately 11 nm in diameter and 1.6 μm in length. Projections from the thick filaments called cross-bridges extend toward the thin filaments. **Cross-bridges** play a fundamental role in muscle contraction.

Thin filaments contain the proteins **actin**, **tropomyosin,** and **troponin** and are approximately 5 nm in diameter and 1μm in length.

Two tubular networks are present in skeletal muscle fibers. **The transverse (T) tubule** is formed as an invagination of the surface of the muscle membrane. Action potential spreading over the surface of the muscle membrane is propagated into the network of the T tubules, which forms specialized contacts with the **SR**, the internal tubular structure that runs between the myofibrils. The SR has a high concentration of Ca^{2+}, which is used to initiate muscle contraction when the muscle is stimulated. The ends of SR expand to form terminal cisternae (TC), which make contact with the T tubule. Small projections, or **foot processes**, span the 20 nm separating the two tubular membranes. The SR-membrane contains a protein called the **ryanodine receptor** that contains the foot process and Ca^{2+} -release channel.

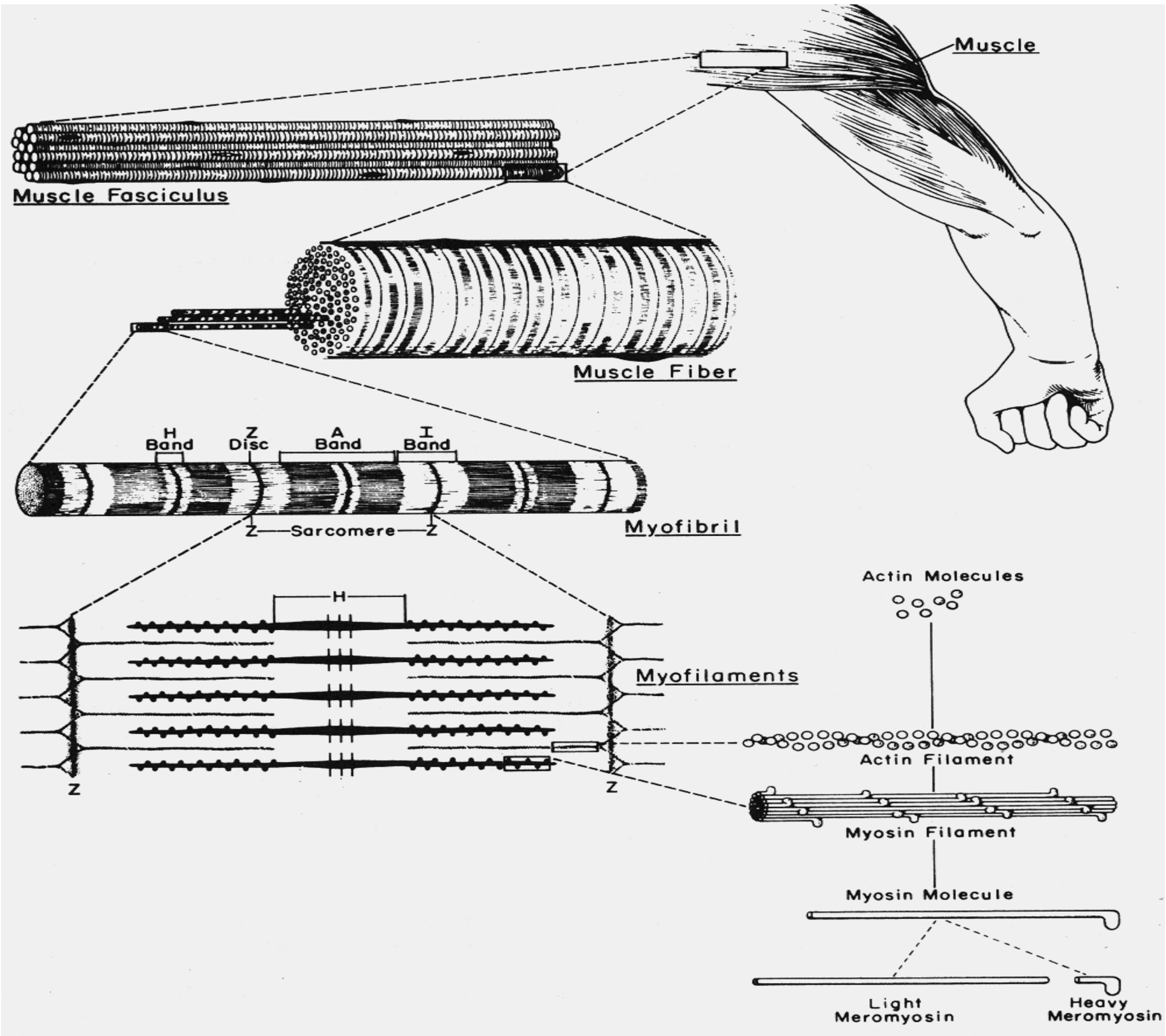

Figure 7

Excitation-contraction coupling. Excitation-contraction (EC) coupling is the process by which an action potential initiates the contractile process. EC coupling involves four steps: the propagation of the action potential into the T tubule and release of Ca^{2+} from the TC, the activation of the muscle proteins by Ca^{2+}, the generation of tension by the muscle proteins, and the relaxation of the muscle.

Action potentials in the muscle cell membrane initiate depolarization of the T tubules. Depolarization of the T tubule causes the ryanodine Ca^{2+} channels to open, which leads to the release of Ca^{2+}. $Ca2^{+}$ flows out of the TC and into the cytoplasm.

For a muscle to contract, the thick and thin filaments must interact. When the cell is at rest, this interaction is inhibited; the influx of Ca^{2+} removes the inhibition. Ca^{2+} binds to troponin on the thin filaments, causing a conformational change in troponin that alters the position of the tropomyosin. The movement of tropomyosin (deeper into the groove of the thin filament) exposes the myosin binding sites on the actin, allowing the myosin cross-bridge on the thick filament to bind to actin on the thin filament. A rise in Ca^{2+} concentration (0.1-10) μmol/l, is sufficient to activate all of the muscle protein within the skeletal muscle fiber.

Generation of tension. The activated muscle proteins undergo repetitive **cross-bridge cycling** during which the muscle uses the energy obtained from the hydrolysis of ATP to shorten and generate tension. The cross-bridge cycle can be divided into four steps.

The **first step** is the binding of the cross-bridge to actin, as described. **Binding occurs spontaneously after** Ca^{2+} binds to troponin.

The **second step** is the bending of the cross-bridge, which pulls the thin filament over the thick filament, generating tension. The energy used to bend the cross-bridge is generated when ATP is hydrolyzed. Both the ATP molecule and the ATPase required for its hydrolysis are located on the cross-bridge; however, ATPase is activated only when myosin binds to actin. Therefore, hydrolysis occurs only during cross-bridge cycle.

The **third step** is the detachment of the cross-bridge from the thin filament. This occurs after the cross-bridge has bent.

In the **fourth step**, the cross-bridge returns to its original upright position. Once there, it can participate in another cycle. Cycling continues as long as Ca^{2+} is bound to troponin.

Relaxation of muscle occurs when the Ca^{2+} is removed from the cytoplasm by Ca^{2+} pumps, located on the SR membrane. When the intracellular Ca^{2+} concentration falls below 0.1 μmol/l, troponin returns to its original conformational state, tropomyosin inhibition of myosin-actin interaction is restored, and cross-bridge cycling stops.

Shortening and force development is produced by the sliding of thin filaments over thick filaments. The contractile properties of muscle can be studied in two types of mechanical conditions: **isometric** and **isotonic** contractions.

The thin filaments are drawn to the center of the sarcomere by the repetitive cycling of cross-bridge. Each time an attached cross-bridge bends, it generates a force that pulls the Z line toward the center of the sarcomere. The force developed by the bending of the cross-bridge is transmitted through the thin filament to the Z line and then through the sarcolemma and tendious insertions of the muscle to the bones.

An **isometric contraction** occurs when the ends of the muscle, or bones, do not move during the contraction; therefore, the length of the muscle remains constant but the tension changes.

When intracellular Ca^{2+} concentration increases to greater than 0.1 μmol/l, cross-bridge cycling causes an increase in muscle force (left ordinate). The resulting force development is the muscle twitch.

If the frequency of stimulation is rapid, individual twitches become one continuous contraction, i.e., a maximal force is generated. The frequency required to produce a maximal force is called a **tetanic frequency,** and the resulting contraction is called **tetanus**.

The force of an isometric contraction can be altered by altering the initial length of the muscle fiber. The **overlap** between the thick and thin filaments determines the number of cross-bridges that will bind to actin when the muscle is stimulated.

At an initial sarcomere length 2.2 μm, each cross-bridge can bind to an actin molecule on the thin filament, a maximum force is generated.

If the muscle is stretched to a sarcomere length of 3.5 μm, there is no overlap between the thick and thin filaments and, therefore, no force develops when the muscle is stimulated.

If the sarcomere shortens to length below 2.0 μm, the thin filaments from opposite sides of the sarcomere interfere with each other and the force of contraction decreases.

If the sarcomere shortens to 1.5 μm, the Z lines abut the thick filaments and no force can be generated.

An **isotonic contraction** occurs when the muscle shortens, therefore, the tension remains constant but the length changes.

The initial portion of the contraction is isometric, because the muscle only begins to shorten when the force developed by the muscle equals the load on the muscle. The weight that a muscle lifts during an isotonic contraction is called the **afterload**.

While the muscle is shortening, the force remains equal to the afterload. The contraction is called **isotonic** because the force remains constant during the contraction.

The velocity of shortening remains constant. The load velocity relationship is an important characteristic of muscle because it indicates that the greatest velocity of shortening is generated when the afterload on the muscle is zero. The peak velocity of shortening is an indication of the cross-bridge cycling speed.

The amount of shortening decreases as the afterload increases. As the muscle shortens below a sarcomere length of 2.2 μm, its ability to generate force decreases. At some length, the maximal force the muscle can develop becomes slightly less than the afterload and shortening stops. The greater the afterload, the longer it takes to reach the maximal force.

Hand grip strength test procedure

CAUTION: If you have high blood pressure (140/90 mmHg) DO NOT perform this test prior to receiving medical clearance to do so. Information provided solely as a reference and should not be performed without proper training or certification.

The purpose of this test is to measure the maximum isometric strength of the hand and forearm muscles. Handgrip strength is important for any sport in which the hands are used for catching, throwing or lifting. Also, as a general rule people with strong hands tend to be strong elsewhere, so this test is often used as a general test of strength.

Hand grip strength is tested by the hand grip dynamometer ДК-50 (fig. 8). The hand grip dynamometer ДК-50 is intended for measurement of hand muscular force at various on age and a physical condition of groups of people. The principle of work of a dynamometer is based on measurement of elastic deformation of a flat spring. The power spring is made of spring steel with a nickel covering, and the case from polyvinylchloride plastic compound.

Figure 8

Procedure. The subject holds the dynamometer in the hand to be tested, with the arm at right angles and the elbow by the side of the body. The handle of the dynamometer is adjusted if required - the base should rest on first metacarpal (heel of palm), while the handle should rest on middle of four fingers. When ready the subject squeezes the dynamometer with maximum isometric effort, which is maintained for about 5 seconds. No other body movement is allowed. The subject should be strongly encouraged to give a maximum effort.

Scoring. The best result from several trials for each hand is recorded, with at least 15 seconds recovery between each effort. The values listed below (in kg and lbs) give a guide to expected scores for adults. These values are the average of the best scores of each hand.

Other protocols will just use the score from the dominant hand, or compare the left and right hand results.

	MALES		**FEMALES**	
rating	**(lbs)**	**(kg)**	**(lbs)**	**(kg)**
excellent	> 141	> 64	> 84	> 38
very good	123-141	56-64	75-84	34-38
above average	114-122	52-55	66-74	30-33
average	105-113	48-51	57-65	26-29
below average	96-104	44-47	49-56	23-25
poor	88-95	40-43	44-48	20-22
very poor	< 88	< 40	< 44	< 20

Validity. The validity of this test as a measure of general strength has been questioned, as the strength of the forearm muscles does not necessarily represent the strength of other muscle groups. If you wish to measure the strength of a particular muscle group, there are other specific tests that can be performed.

Reliability. The dynamometer may need to be calibrated regularly to ensure consistent results. Having consistent technique and adequate rest is required to ensure reliability.

Advantages. This is a simple and commonly used test of general strength level, well researched and many norms are available.

Disadvantages. The dynamometer must be adjusted for hand size, how successfully this is done will affect the accuracy of the measurement.

Comments. It is also useful to record whether the athlete is left or right handed, as this may help in the interpretation of results. The non-dominant hand usually scores about 10% lower.

The forearm muscles are easily fatigued, so the best scores are usually achieved in the first or second trial.

Results are expected to differ between male and females, between left and right (dominant and non-dominant) hands, and with age. The results can also be affected by the position of the wrist, elbow and shoulder, so these should be standardized. There are many other factors to consider.

Lab test protocol
NOTE! Copy protocol

1. Calculate and write down (Table 1) the relative strength of each hand:
$\mathbf{F_{relative} = 100\,(F_{max}/mg)}$, where m, kg – tested person mass, g = 9.8 m/s^2. **1 дН = 10 N**

Table 1

Right hand grip strength, N	F_{1r}	F_{2r}	F_{3r}	F_{4r}	$F_{max\,r}$	$F_{relative\,r}$
Left hand grip strength, N	F_{1l}	F_{2l}	F_{3l}	F_{4l}	$F_{max\,l}$	$F_{relative\,l}$

2. Calculate and write down (Table 2) for each hand:
- **work capacity of forearms muscles**: $\mathbf{P = (F_1 + F_2 + \ldots + F_{10})/10}$, **N**;
- **diminution index of forearms muscles work capacity:** $\mathbf{S = (F_1 - F_{min})/F_{max}}$

Table 2

Right hand grip strength, N	$F_{max\,r}$	F_{1r}	F_{2r}	F_{3r}	F_{4r}	F_{5r}	F_{6r}	F_{7r}	F_{8r}	F_{9r}	F_{10r}	$F_{min\,r}$	P_r	S_r
Left hand grip strength, N	$F_{max\,l}$	F_{1l}	F_{2l}	F_{3l}	F_{4l}	F_{5l}	F_{6l}	F_{7l}	F_{8l}	F_{9l}	F_{10l}	$F_{min\,l}$	P_l	S_l

Analysis and conclusions
1.
2.
3.