

Tendon-driven hand: teaching pack

Version 2.5 · as of 6 October 2026 · five teaching units on mechanics, motion and measurement

In five units the pack leads from the force in a cable drive to the motion program of a hand with six actuators. It uses two tools that run in the browser and install nothing: the tendon hand calculator ([index.html](#)) and the motion test bench ([pruefstand.html](#)). A printed model is not required; two units contain an experiment with string, a pen and a kitchen scale.

Audience. Upper secondary classes with a technical focus, technical colleges, first-year mechanical engineering and mechatronics, workshops and maker courses. Prerequisites: the law of the lever, trigonometric functions and basic spreadsheet skills.

Status. The hand this pack refers to is a design draft. It has been designed and checked by calculation, but it has not been printed or measured. All figures are calculated values. Unit 5 shows where the model reaches its limits; that is part of the subject matter.

Not a medical device. The hand is a robot end effector for teaching, experiments and research. It is not intended for use on or in the human body and it is not a prosthesis.

Disclosure. This teaching pack comes from a business that earns money with additive manufacturing. Keep this in mind wherever manufacturing methods are compared.

Unit	Topic	Duration	Tool
1	From torque to force at the fingertip	50 minutes	calculator
2	Friction at a deflection	50 to 100 minutes	string, pen, kitchen scale, calculator
3	Tendon travel and actuator angle	50 minutes	calculator, pocket calculator
4	Programming motion	100 minutes	motion test bench
5	From model to machine	50 to 100 minutes	both tools

Unit 1: From torque to force at the fingertip

Learning goals. Learners explain how the torque of a servo becomes a pulling force in the tendon and then a force at the fingertip. They distinguish stall torque from continuous duty.

Content. A spool of radius r_S turns the actuator torque M into the tendon force $F_S = M / r_S$. In continuous duty a servo may deliver only part of its stall torque; the calculator uses the factor $k_D = 0.25$. At the joint the tendon acts with the lever arm r_G , the load acts with the lever h . Losses at deflections are summed up in the efficiency η :

$$F = k_D \cdot (M / r_S) \cdot \eta \cdot r_G / h$$

Procedure. Open the calculator and choose stage B. Look at the inputs: stall torque 1.9 Nm, spool radius 9 mm, joint radius 8 mm, lever to the fingertip 85 mm.

Tasks.

1. Calculate the tendon force in continuous duty by hand and compare with the calculator.
2. Calculate the continuous force at the fingertip using the efficiency shown by the calculator.
3. Halve the spool radius in the calculator. What happens to the force, what happens to the actuator angle? Give reasons.
4. The manufacturer states the stall torque. Why is it unsuitable as a design value for a hand that holds an object?

Solutions.

1. $F_S = 0.25 \cdot 1.9 \text{ Nm} / 0.009 \text{ m} = 52.8 \text{ N}$.
2. $F = 52.8 \text{ N} \cdot 0.885 \cdot 8 \text{ mm} / 85 \text{ mm} = 4.4 \text{ N}$. With the full stall torque it would be 17.6 N, but only for a short time.
3. The force doubles, and so does the actuator angle for the same tendon travel. Force and travel trade off through the radius; the work stays the same.
4. At stall the motor stands still, draws its highest current and heats up. Holding is continuous duty; what counts is the torque the actuator delivers without overheating.

Extension. The same calculation for stage A: the continuous force is about 0.25 N. Discussion: what is that enough for, and what not?

Unit 2: Friction at a deflection

Learning goals. Learners measure the loss of force of a string at a fixed deflection, describe it with the capstan equation and explain why pulleys with bearings do better than sliding guides.

Content. If a string runs over a fixed cylinder with wrap angle θ , the ratio of the forces on both sides follows the capstan equation (Euler-Eytelwein): $F_{\text{out}} / F_{\text{in}} = e^{(-\mu\theta)}$, θ in radians. For $\mu = 0.2$ and a deflection of 90° this gives 0.73. Several deflections multiply.

Experiment. Material: string, a round pen or metal rod, a weight of about 200 g, a kitchen scale with a hook or a spring balance. The weight hangs on the string, the string runs over the horizontally clamped pen, the scale pulls at the other end. Read the force at which the weight just begins to rise and the force at which it just begins to sink. Repeat with 90° , 180° and one additional full turn.

Tasks.

1. From raising and lowering at 180° , determine the friction coefficient μ . Hint: when raising, $F_{\text{pull}} = G \cdot e^{(\mu\theta)}$; when lowering, $F_{\text{pull}} = G \cdot e^{(-\mu\theta)}$.
2. With your μ , predict the forces at 90° and at 540° and check them in the experiment.
3. In the calculator, stage B has four deflections over pulleys with bearings and the efficiency 0.885. What is the efficiency of a single pulley? What efficiency would four fixed pins give with your μ at 90° each?

Solutions.

1. From the ratio of the two readings: $F_{\text{raise}} / F_{\text{lower}} = e^{(2\mu\theta)}$, so $\mu = \ln(F_{\text{raise}} / F_{\text{lower}}) / (2\theta)$ with $\theta = \pi$. Typical results for cotton string on wood or steel lie between 0.15 and 0.35.
2. Own values; the deviation between prediction and measurement belongs in the report.

3. Single pulley: fourth root of 0.885, which is 0.97. Four pins with $\mu = 0.2$ and 90° each: 0.73 to the fourth power, which is 0.28. Less than a third of the force would remain.

Extension. Run the same string through a piece of PTFE tube and lay the tube in a bend. How does the force change with the bend angle? The hand in the draft guides its tendons to the drive unit in such tubes; the loss in them has been calculated but not measured yet. The graphic "Friction in the tube" shows the calculation for three guides.

Unit 3: Tendon travel and actuator angle

Learning goals. Learners calculate how much tendon a joint takes up when it flexes, and check whether the range of an actuator is sufficient.

Content. If the tendon runs on a circular path of radius r around the joint axis, the travel is $s = r \cdot \theta$. If it runs freely from one exit to the next, both at distance a from the axis and at distance r below it, the span shortens during flexion by

$$s = 2a \cdot (1 - \cos(\theta/2)) + 2r \cdot \sin(\theta/2)$$

The spool of radius r_S has to turn by $\varphi = s / r_S$ (in radians).

Tasks.

1. For $r = a = 8 \text{ mm}$ and $\theta = 90^\circ$, calculate the travel on the circular path and the travel of the free tendon.
2. One tendon flexes three joints by 90° each. What is the tendon travel with free routing, and by what angle does a spool of 9 mm radius turn?
3. A servo has a range of 180° . What minimum spool radius does it need for the travel from task 2? What does that mean for the force (unit 1)?
4. Check task 2 in the motion test bench: machine "Hand with six actuators", set the index finger actuator to 90° by hand and read tendon travel and actuator angle.

Solutions.

1. Circular path: $8 \text{ mm} \cdot \pi/2 = 12.6 \text{ mm}$. Free tendon: $2 \cdot 8 \text{ mm} \cdot (1 - \cos 45^\circ) + 2 \cdot 8 \text{ mm} \cdot \sin 45^\circ = 16.0 \text{ mm}$.
2. $3 \cdot 16.0 \text{ mm} = 48.0 \text{ mm}$; $\varphi = 48.0 \text{ mm} / 9 \text{ mm} = 5.33$ in radians, which is 306° .
3. $r_S = s / \varphi = 48.0 \text{ mm} / \pi = 15.3 \text{ mm}$. The larger radius lowers the tendon force in the same ratio.
4. The test bench shows 48.0 mm and 306° ; the range of 360° is sufficient.

Unit 4: Programming motion

Learning goals. Learners write motion sequences in a simple command language, read error messages, distinguish sequential from simultaneous motions and read from the actuator table what the actuators have to do.

Content. The motion test bench describes a machine as chains of joints and links. A program sets actuators:

Command	Effect
<code>flex TARGET VALUE in SECONDS</code>	sets an actuator or a group to the value
<code>extend TARGET in SECONDS</code>	back to the rest position
<code>wait SECONDS</code>	pause
<code>together ... end</code>	all commands in the block start at the same time
<code>repeat COUNT ... end</code>	repeats the block
<code># text</code>	comment

The German command words (beuge, strecke, warte, zugleich, wiederhole, ende) work as well; the example programs use them. The test bench calculates positions. It does not calculate forces, weight or collisions between parts.

Procedure. Choose the machine "Hand with six actuators", load the program "Counting" and run it. Then work on the tasks in pairs.

Tasks.

1. Change "Counting" so that the fingers extend in reverse order, starting with the little finger.
2. Write a program that closes and opens the fist three times in a row. Use `repeat`.
3. Put the line `flex zeige 120` into a program. What does the test bench report, and why is the limit useful?
4. Load the program "Fist" and read from the actuator table: which actuator turns furthest? How many degrees per second does it have to deliver?
5. Shorten the time for closing the fingers to 0.5 seconds. What angular speed does that require? According to the vendor, the bus servo assumed here turns at 270° per second without load at 12 V, and more slowly under load and at lower voltage. What follows?

Solutions.

1. The four `strecke` lines in the order klein, ring, mittel, zeige.
2. For example:

```
repeat 3
  flex finger 84 in 1.0
  extend finger in 1.0
end
```

3. The test bench rejects the line with its line number because the joint only flexes up to its stop. Limits in the description prevent a program from demanding a position the mechanism cannot take.
4. The flexor tendons of the fingers: 283° in 1.2 seconds, which is 236° per second.
5. 283° in 0.5 seconds is 566° per second, more than the actuator delivers. On the device the motion takes longer than in the program. The simulation shows what is demanded, not what the actuator can do.

Extension. Load other machines (gripper, excavator arm, eight-arm machine, gantry) and describe which building blocks they share with the hand. These machines are concepts, not designs. The actuator table can be saved as a file with the button below it; a controller builds the actuator commands from it.

Unit 5: From model to machine

Learning goals. Learners name what a calculation model leaves out, plan a measurement to check it and explain what stays the same and what changes when a machine is scaled up.

Content. Each of the two tools leaves something out. The calculator knows friction only as a fixed efficiency, tendon stretch only as a spring and the strength of the printed parts not at all. The test bench knows no forces. Only a measurement on the built part shows how good the assumptions are. In between lies rigid-body simulation: the folder `urdf` holds every machine in a format such programs read. They calculate weight, forces and contact, but with simplified masses and without tendons.

When scaling by a factor k , lengths grow with k , areas with k^2 , volume and mass with k^3 . An arm twice as long weighs eight times as much in the same material; its load-bearing cross-section grows only fourfold. Angles, ratios and the relation of tendon travel to joint radius stay the same.

Tasks.

1. List three assumptions of the calculator that a measurement could refute, and state for each how you would measure.
2. A finger of the model is built at a scale of 3:1 in steel instead of plastic. Density rises from about 1.3 to about 7.9 g/cm³. By what factor does the mass rise? By what factor does the moment from its own weight at the base joint rise?
3. Which quantities of the hand do not change when scaling up? What does that mean for the motion program?
4. The human hand flexes its fingers with muscles in the forearm; the force arrives through tendons. What are the advantages of this arrangement, and what is its price? Compare with the hand in the draft, whose actuators sit remotely.

Solutions.

1. For example: efficiency of the deflection (measure the force at the fingertip with a scale and compare with the calculated value); tendon stretch (measure the joint angle under load); usable continuous torque (servo temperature over time).
2. Mass: $3^3 \cdot 7.9 / 1.3$, about 164 times. Moment from its own weight: the lever times 3 in addition, about 492 times.
3. Joint angles, actuator angles if the spool is scaled as well, and the sequence of motions. The program remains valid; times and forces have to be designed anew.
4. Advantages: light fingers, low moving mass, room for strong actuators. Price: long tendons with friction and stretch, coupling of the joints across the wrist, effort for routing.

Notes for teachers

- The tools run without a network connection from a folder; they store nothing and send nothing.
- Each unit can be taught on its own. Unit 3 builds on unit 1, unit 5 sums up.
- The experiments in unit 2 use weights up to about 200 g and need no special protective measures. Do not wrap strings around fingers.
- For those who want to continue after unit 5: the same folder holds six workshop exercises (EXERCISES_Workshop_en.md). There, learners build their own machines from the building blocks of the finger; the workshop checks the solutions itself.
- For those who want to build the hand: the design is an unprinted draft. A kit and print files are not part of this pack.
- Assessment: the solutions to the calculation tasks are in the text; the open tasks (unit 2 no. 2, unit 5 nos. 1 and 4) are assessed by reasoning, not by result.

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Text: all rights reserved. The two tools are under the MIT licence. The hand and the machines derived from it serve civil purposes in teaching, experiments and research; they are not available for armaments and weapons.