Bionic limb prosthetics

From neural signals to robotic movement

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MICRO - 568
Seminar in physiology and instrumentation

EPFL

REFERENCES

Here's all the sources used to create this presentation:

1. The global burden of traumatic amputation in 204 countries and territories.
2. **Guyton**, Chapters on Muscle Physiology and Motor Control
3. Advances in prosthetic technology: a perspective on ethical considerations for development and clinical translation
4. Estimating the prevalence of limb loss in the United States: 2005 to 2050
5. Estimating Recent US Limb Loss Prevalence and Updating Future Projections
6. References for illustration can be found in the **BIBLIOGRAPHY** slide

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SUMMARY

PROBLEM

Loss of upper or lower limb due to trauma, disease, or congenital reasons.

OBJECTIVES

Replace missing limb function with devices that restore **mobility, dexterity,** and **independence**.

APPROACH

Integration of physiology (muscle, nerves, biomechanics) with instrumentation (sensors, actuators, AI).

TABLE OF CONTENTS

1. INTRODUCTION

- Limb amputation → major disability worldwide (~57 million people with limb loss globally).

- Modern bionic prostheses go beyond cosmetic replacement: they aim to **restore motor function** and **sensory feedback**.

- Importance: understanding neuromuscular physiology (nerve signals, muscle contraction, proprioception).

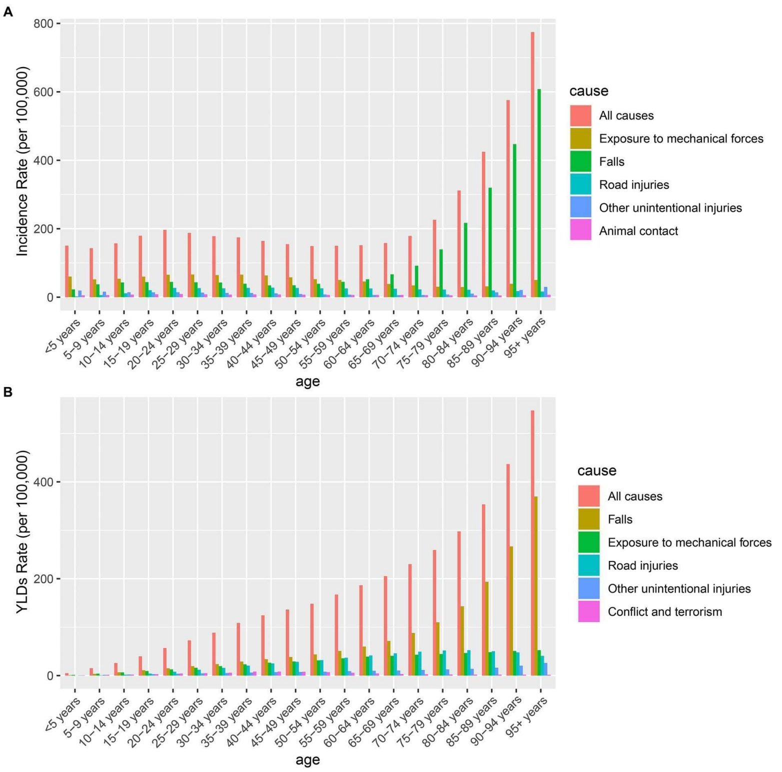


Illustration* [1] *: (A)* *The top five causes and all causes for the incidence rate of traumatic amputation in different age groups.
(B) *The top five causes and all causes for YLDs rate of traumatic amputation in different age groups. YLDs, years lived with disability.*

INTRODUCTION

Example : US Epidemiology

- The total number of people with limb loss in the US is projected to double by 2050.
- The US currently has approximately 2.1 million people living with an amputation.
- An estimated 185,000 new amputations are performed each year.

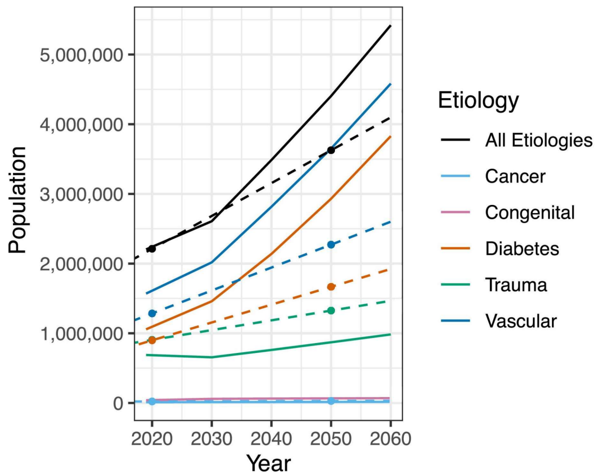


Illustration [5] : *Projected prevalence of limb loss by etiology*

Primary Causes of Amputation	Percentage	Context
Vascular Disease (diabetes, peripheral artery disease)	54%	This is the leading cause of amputation, driving the overall growth in prevalence due to rising chronic disease rates.
Trauma (accidents, injuries)	44%	Represents the second major cause, including road accidents and occupational injuries.

2. PHYSIOLOGY ASPECTS

Key physiological parameters [2] :

- Motor signals: Electromyography (EMG) potentials from residual muscles (~µV to mV).
- Sensory feedback: Touch, pressure, proprioception.
- Biomechanics: Torque, joint angles, gait cycle (for legs).
- Metabolic demand: Energy cost of walking with/without prosthesis.

What we want to control, repair, measure:

- Control of artificial joints from nerve or muscle signals.
- Measurement of forces and positions.
- Repair of lost motor/sensory function.

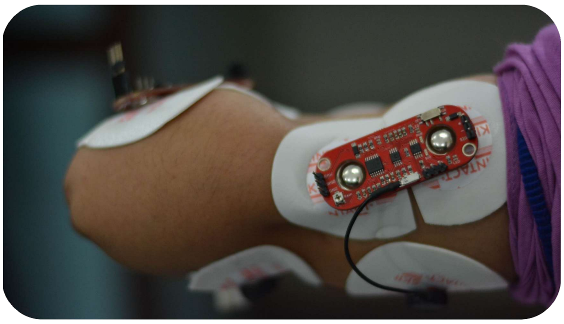
Medical significance:

- Loss of limb function = reduced autonomy, mobility, mental health impact.
- Bionics reduce long-term complications (back pain, arthritis due to gait asymmetry).

3. TECHNICAL DESCRIPTION

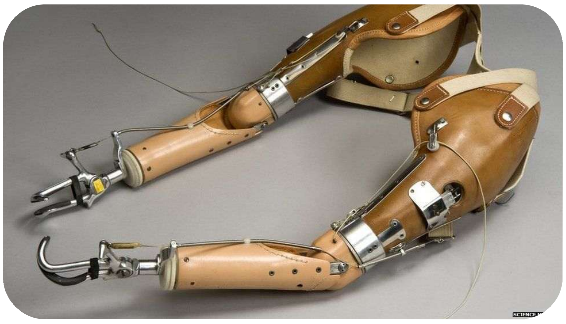
Mode of action :

- Myoelectric control (EMG sensors on residual muscle).
- Direct neural interfaces (brain-machine, peripheral nerve electrodes).
- Actuators : electric motors, hydraulic/pneumatic systems.
- Power sources : Li-ion batteries.



Comparison of principles :

- Traditional prosthesis : purely mechanical (body-powered).
- Myoelectric prosthesis : TMR or EMG → movement.
- Advanced bionics : bidirectional (motor + sensory feedback).



4. SPECIFICATIONS

Ottobock Michelangelo Hand

- Grip patterns: 7+
- Weight: ~520 g
- Battery life: 1 day

Össur Rheo Knee / C-Leg

- Real-time microprocessor control (gait adaptation).
- Walking speed range: 0.8 – 2.4 m/s.

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5. CLINICAL APPLICATIONS

Post-amputation rehabilitation.

Used in trauma, vascular disease, cancer patients, war veterans.

FDA regulatory pathway:

- Class II/III medical device approval.
- Clinical trials emphasize safety, robustness, reliability.

Guidelines : devices used under physiotherapist + rehab physician supervision.

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REHABILITATION & MAINTENACE

Goal → maximize the functional integration and comfort of the bionic device.

User training

- **Motor control :** learning muscle contraction patterns (EMG) to command joints and grips.
- **Sensory Input :** training to interpret feedback signals (haptics, artificial proprioception) when available.
- **Daily Routine :** Managing battery (daily charging) and donning/doffing procedures.

Device maintenance

- **Durability :** devices are designed for daily use (trauma, moisture).
- **Service :** Requires regular maintenance (sensor calibration, software updates, component replacement).
- **Challenges** : breakdowns, high cost of repairs, and device downtime.

REHABILITATION & MAINTENACE

Limitations of Current Prosthetic Devices

- Despite technological progress, prosthetic devices still lack the strength and flexibility of natural hands.
- Movements are often restricted to predefined gestures.
- Many users experience their prosthesis as a ”foreign body”, indicating low embodiment.
- The use of a prosthesis can increase the risk of musculoskeletal complications, such as: osteoarthritis, back pain

6. PRODUCT ASPECTS

COST

Bionic arm : $20,000 - $100,000

Bionic leg : $30,000 - $120,000

KEY PLAYERS

Ottobock, Össur, Open Bionics, DEKA Arm (FDA approved).

MARKET TREND

Rapid growth (driven by AI + robotics).

MODE OF USES

Rechargeable, daily use, controlled via training.

ETHICAL & SOCIETAL CONSIDERATION

Accessibility and cost

- Economic Burden: Very high cost ($20,000 to $120,000+), creating a major disparity in access.
- Coverage: Variable insurance and reimbursement policies; often, the most advanced options are not fully covered.

Autonomy and bodily integrity

- Consent: Ethical questions raised by invasive neural interfaces (BCI/implants).
- Enhancement (Augmentation): The blurred line between ”restoration” and ”enhancement” of human capabilities (transhumanism).

ETHICAL & SOCIETAL CONSIDERATION

Future Technological Challenges

- Data Security: Protecting neurological data and AI-decoded control patterns.
- Tech Dependency: Psychological impact of relying on charging, updates, and technical reliability.

Social Acceptance

- Stigma: Public perception of advanced bionic technologies.
- Normalization: Need for standardization of care and integration into society and the workplace.

7. CONCLUSION

Limitations:

- High cost.
- Limited sensory feedback.
- Battery constraints.

Technology trends:

- Neural implants & brain-computer interfaces (Elon Musk's Neuralink, DARPA projects).
- Regenerative medicine combined with bionics (biohybrid limbs).
- AI-driven adaptive control.

New approaches:

- Direct cortical decoding of movement.
- Integration of haptics + proprioception.

Illustration : *Concept art of future fully integrated bionic limb with brain control.*

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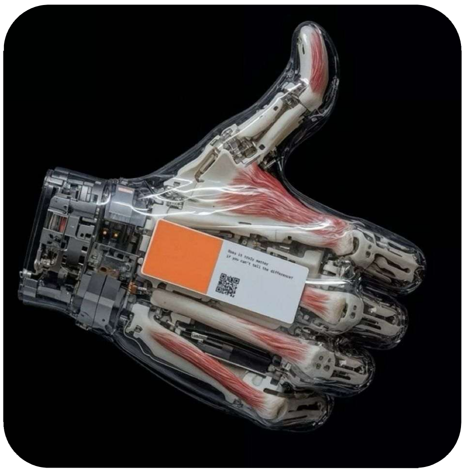

THANK YOU

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Q&A

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APPENDIX

LEG DOFs

Joint Complex	Degrees of Freedom (DoF)	Description of Movement
Pelvis	6 DoF	Translation (3) and Rotation (3) relative to the hip joints.
Hip Joint	3 DoF	Flexion/Extension, Abduction/Adduction, Internal/External Rotation.
Knee Joint	2 DoF	Primarily Flexion/Extension, plus some Internal/External Rotation.
Ankle Joint	2 DoF	Plantarflexion/Dorsiflexion (up/down) and Inversion/Eversion (side-to-side).
Foot/Toes	11 DoF	Distributed across the subtalar, midtarsal, and metatarsal joints, allowing the foot to adapt to varied terrain.
Total	**24 DoF**	**Total for a single, complete leg and half-pelvis model.**

HAND DOFs

Structure	Degrees of Freedom (DoF)	Description of Movement
Wrist	2 DoF	Flexion/Extension and Radial/Ulnar Deviation.
Fingers (4 total)	3DoF per finger x4	Flexion/Extension at the MCP, PIP, and DIP joints.
Thumb	5 DoF	Flexion/Extension, Abduction/Adduction, and Rotation (Opposition).
Total (excluding wrist)	**22 DoF**	For the fingers and thumb alone.

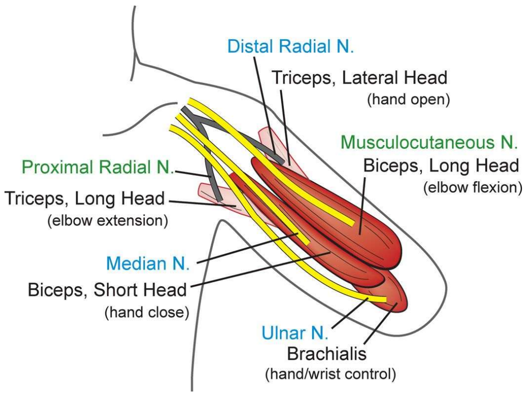
TARGETED MUSCLE REINNERVATION

TMR is a surgical advance that drastically improves the interface between the user's nervous system and the bionic device.

What is TMR? It's a surgical technique where nerves that previously controlled the amputated limb are surgically **rerouted to reinnervate small, denervated muscles** (often chest or arm muscles) on the residual limb.

Benefit for Motor Control:

- It provides **multiple, independent electromyography (EMG) control sites**, allowing the user to generate up to 4-6 distinct control signals (e.g., open hand, close hand, wrist pronation, wrist supination) with the same muscle group.
- This results in a far more **intuitive control scheme**, minimizing the need for the user to cycle through predefined gestures.

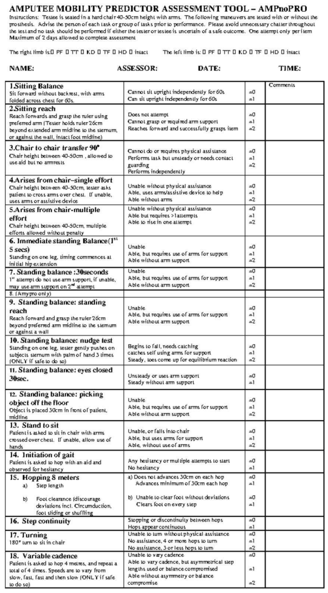


Potential for Sensory Feedback: TMR creates new **neuromuscular interfaces** that, when stimulated (e.g., via a haptic feedback system), can sometimes be interpreted by the brain as coming from the phantom hand. This addresses the "foreign body" sensation by enhancing **proprioception** and the feeling of **embodiment**.

THE K-LEVEL SYSTEM (AMPUTEE MOBILITY PREDICTOR)

This system is essential for clinical practice and product prescription in the lower limb market.

- **Purpose:** The K-level system (or Amputee Mobility Predictor, AMPPRO) is a standardized scale used by clinicians and insurance providers to **rate a patient's potential for ambulation** and functional ability.
- **Role in Prescription:** A patient's K-level directly dictates the complexity and cost of the prosthetic components (e.g., feet, knees) that they are eligible to receive for reimbursement.



AMPUTEE MOBILITY PREDICTOR ASSESSMENT TOOL – AMPnoPRO

Instructions: Testee is seated in a hard chair 40-50cm height with arms. The following maneuvers are tested with or without the prosthesis. Advise the person of each task or group of tasks prior to performance. Please avoid unnecessary chatter throughout the test and no task should be performed if either the tester or testee is uncertain of a safe outcome. One attempt only per item Maximum of 2 days allowed to complete assessment

The right limb is: ☐ PF ☐ TT ☐ KD ☐ TF ☐ HD ☐ intact   The left limb is: ☐ PF ☐ TT ☐ KD ☐ TF ☐ HD ☐ intact

NAME: **ASSESSOR:**   **DATE:**   **TIME:**

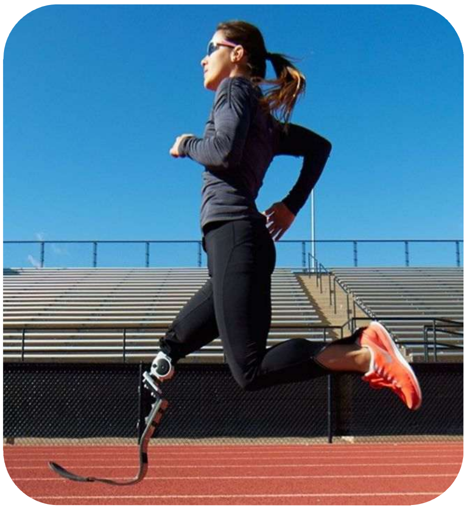
1.Sitting Balance Sit forward without backrest, with arms folded across chest for 60s.	Cannot sit upright independently for 60s Can sit upright independently for 60s	=0 =1	Comments
2.Sitting reach Reach forwards and grasp the ruler using preferred arm (Tester holds ruler 26cm beyond extended arm midline to the sternum, or against the wall, intact foot midline)	Does not attempt Cannot grasp or required arm support Reaches forward and successfully grasps item	=0 =1 =2	
3.Chair to chair transfer 90° Chair height between 40-50cm , allowed to use aid but no armrests	Cannot do or requires physical assistance Performs task but unsteady or needs contact guarding Performs independently	=0 =1 =2	
4.Arises from chair–single effort Chair height between 40-50cm, tester asks patient to cross arms over chest. If unable, uses arms or assistive device	Unable without physical assistance Able, uses arms/assistive device to help Able without arms	=0 =1 =2	
5.Arises from chair-multiple effort Chair height between 40-50cm, multiple efforts allowed without penalty	Unable without physical assistance Able but requires >1attempts Able to rise in one attempt	=0 =1 =2	
6. Immediate standing Balance(1st 5 secs) Standing on one leg, timing commences at initial hip extension	Unable Able, but requires use of arms for support Able without arm support	=0 =1 =2	
7. Standing balance :30seconds 1st attempt do not use arm support, if unable, may use arm support on 2nd attempt	Unable Able, but requires use of arms for support Able without arm support	=0 =1 =2	
8. (Amypro only)			
9. Standing balance: standing reach Reach forward and grasp the ruler 26cm beyond preferred arm midline to the sternum or against a wall	Unable Able, but requires use of arms for support Able without arm support	=0 =1 =2	
10. Standing balance: nudge test Standing on one leg, tester gently pushes on subjects sternum with palm of hand 3 times (ONLY if safe to do so)	Begins to fall, needs catching catches self using arms for support Steady, toes come up for equilibrium reaction	=0 =1 =2	
11. Standing balance: eyes closed 30sec.	Unsteady or uses arm support Steady without arm support	=0 =1	
12. Standing balance: picking object off the floor Object is placed 30cm in front of patient, midline	Unable Able, but requires use of arms for support Able without arm support	=0 =1 =2	
13. Stand to sit Patient is asked to sit in chair with arms crossed over chest. If unable, allow use of hands	Unable, or falls into chair Able, but uses arms for support Able, without use of arms	=0 =1 =2	
14. Initiation of gait Patient is asked to hop with an aid and observed for hesitancy	Any hesitancy or multiple attempts to start No hesitancy	=0 =1	
15. Hopping 8 meters a) Step length b) Foot clearance (discourage deviations incl. Circumduction, foot sliding or shuffling	a) Does not advances 30cm on each hop Advances minimum of 30cm each hop b) Unable to clear foot without deviations Clears foot on every step	=0 =1 =0 =1	
16. Step continuity	Stopping or discontinuity between hops Hops appear continuous	=0 =1	
17. Turning 180° turn to sit in chair	Unable to turn without physical assistance No assistance, 4 or more hops to turn No assistance, 3 or less hops to turn	=0 =1 =2	
18. Variable cadence Patient is asked to hop 4 metres, and repeat a total of 4 times. Speeds are to vary from slow, fast, fast and then slow (ONLY if safe to do so)	Unable to vary cadence Able to vary cadence, but asymmetrical step lengths used or balance compromised Able without asymmetry or balance compromise	=0 =1 =2	

Illustration : *Amputee mobility predictor assessment tool.*

THE K-LEVEL SYSTEM (AMPUTEE MOBILITY PREDICTOR)

K-Level	Mobility Potential	Examples of Eligible Components
K0	No ability to transfer or ambulate.	None; prosthesis is not medically necessary.
K1	Fixed/limited speed for household ambulation.	Basic mechanical components; fixed-axis knee.
K2	Ambulates at fixed speed on limited, varied terrain.	Single-axis knee; flexible-keel foot.
K3	Ambulation with varied cadence (speed) outdoors; therapeutic exercise.	**Microprocessor Knees (MPK)**; dynamic response feet (e.g., your Össur Rheo Knee)[4].
K4	Exceeds K3 capacity; high impact, high energy demand (athlete, child).	Highly advanced, often custom components.

USE IN SPORT & HIGH IMPACTS ACTIVITIES



High-Performance Sport Dominance: For activities like competitive running, specialized, non-bionic carbon fiber blades (e.g., Cheetah blades) remain the dominant technology .
These devices are preferred due to their inherent lightweight structure, mechanical energy return (acting like a spring), and superior durability under extreme load.

Bionic Integration in Sport: Advanced bionic knees (like the Össur Rheo Knee mentioned in your specifications) are used for everyday mobility and can adapt to varied terrains.
They utilize real-time microprocessor control to adjust hydraulic damping during activities like cycling, hiking, or traversing uneven ground.

Challenges of Bionic Limbs in Sport: Bionic limbs face significant constraints regarding battery power, waterproofing, and shock absorption required for high-impact activities.
Upper limb bionic hands may be too delicate or slow, leading many users to rely on specialized mechanical attachments (e.g., for swimming, weightlifting, or rock climbing) rather than complex electronic hands.

ETHICAL DEBATE : RESTORATION vs. ENHANCEMENT

Restoration (Therapeutic Use): The primary and medically accepted goal is to use bionic technology to restore a user's lost function back to the level of natural human capacity.
Example: Giving an amputee a hand capable of holding a cup and writing.

Enhancement (Transhumanism): This refers to designing a device that provides capabilities that exceed natural human limits.
Example: A prosthetic arm with superhuman lifting strength, integrated digital displays, or embedded communication devices.

Key Ethical Concerns:
- Equity: If these advanced devices blur the line into enhancement, should they be covered by insurance, given that basic, therapeutic devices are already highly expensive and inaccessible to many?
- Bodily Integrity: The use of invasive technologies, like Brain-Computer Interfaces (BCI), to unlock superior functionality raises significant questions about consent and the definition of bodily autonomy.

PERFORMANCE

Lower Limb Performance (Gait and Mobility)

Lower limb performance is typically measured using gait analysis metrics to quantify natural movement and efficiency.

- **Timed Walk Tests:** Measures like the **10-Meter Walk Test (10mWT)** and **6 Minute Walk Test (6MWT)** objectively assess walking speed and endurance.
- **Mobility Predictors:** The **Amputee Mobility Predictor (AMPPRO)** assesses functional capacity and mobility level (K-level).
- **Balance and Agility:** Tests like the **Timed Up and Go (TUG)** and **Four Square Step Test (FSST)** measure balance, turning ability, and fall risk.
- **Gait Symmetry:** Advanced studies use metrics like **Impulse Symmetry** (comparing ground reaction forces between the prosthetic and sound side) and **Leg Work** (positive mechanical work done on the center of mass) to quantify how natural the gait is. A value of zero indicates complete symmetry.

PERFORMANCE

Upper Limb Performance (Dexterity and Control)

Upper limb performance focuses on control, speed, and functional use in daily activities.

- **Task Scores:** Simple measures include **task completion time** (e.g., how fast a user can move objects across a barrier) and **success rate** for complex functional tasks.
- **Control Characteristics:** Detailed metrics assess **control characteristics** such as **grip aperture plateau** duration and the number of unwanted **wrist rotation adjustments** during movement, which indicate the intuitiveness and precision of the control system (like myoelectric pattern recognition).
- **Grip Force and Speed:** Quantitative data on device specifications, such as the maximum **grip force** (e.g., 152\N} for a specific model) and **closing speed** (e.g., 0.8 seconds), are used to compare functional capacity.