DEPARTMENT OF BIOMEDICAL ENGINEERING

Unit III

Rehabilitation Engineering • Brain-Computer Interface (BCI) Fundamentals • AI-Assisted Medical Devices

No.	Topic	Main subtopics
8	Rehabilitation Engineering	Impairment, disability and handicap; visual, hearing, speech and locomotor disability; assistive devices
9	Brain-Computer Interface (BCI) Fundamentals	Working principle, components, types, signals, imaging techniques, applications, challenges
10	AI-Assisted Medical Devices	Sense–comprehend–act–learn, diagnostics, closed-loop therapy, wearables, prosthetics, barriers, outlook

TOPIC 8
Rehabilitation Engineering

† **Rehabilitation engineering** is the application of engineering science and design to develop technological solutions and devices that help people with disabilities to live independently, take part in education, work and social life, and improve their quality of life. It works through a team: rehabilitation engineer, physiatrist, physiotherapist, occupational therapist, prosthetist/orthotist, audiologist and speech-language pathologist, special educator and, above all, the person with the disability.

8.1 Impairment, disability and handicap

According to the World Health Organization (WHO), the sequence of events leading to disability and handicap is: **injury/disease → impairment → disability → handicap**.



Fig. 8.1 *WHO sequence from injury or disease to handicap.*

Term	Meaning	Example
Impairment	Any loss or abnormality of psychological, physiological or anatomical structure or function.	Loss of a finger; loss of conduction of impulse in the heart; loss of a brain chemical leading to parkinsonism
Disability †	Restriction or lack of ability to perform an activity in the manner or range considered normal, resulting from an impairment.	Cannot grasp objects or walk
Handicap †	Disadvantage resulting from an impairment or disability that limits or prevents a person from fulfilling a normal role.	Cannot travel to work or attend school

† Current WHO practice (ICF) describes the same ideas as impairment of body function/structure, ***activity limitation*** *and* ***participation restriction****.*

The main types of impairment are **vision, hearing, speech, mobility and intellectual (mentally challenged)**.

8.2 Visual impairment

A person who is blind may face problems of attachment, is unable to use the hand as an organ of perception, has difficulty with locomotion, depends on parents or caregivers, may show behavioural problems, and has less social interaction and involvement in activities.

Management: physiotherapy, orientation and mobility instructors, mobility aids and guides, and **Braille technology**. † Other aids include the long (white) cane, screen readers, magnifiers and audio books.

8.3 Hearing impairment

Hearing impairment is a generic term covering the entire range of hearing loss. The degree of loss is graded in decibels (dB):

	Conductive hearing loss	Sensorineural hearing loss
Site / cause	Sound is not conducted efficiently through the outer or middle ear	Damage to the inner ear
Effect	Reduction in sound level	Reduction in sound level; speech understanding suffers, hard to hear clearly
Treatment	Often corrected by medicine or surgery	Cannot be corrected medically; permanent loss
Causes	Impacted ear wax, fluid in the middle ear, ear infections	Birth injuries, genetics, viruses, head trauma, ageing, noise exposure, tumours

Management: sign language; hearing devices such as hearing aids, assistive listening devices and **cochlear implants**; lip-reading skills; speech therapy; and written or printed text. † A hearing aid amplifies sound (microphone, amplifier, receiver); a cochlear implant bypasses the damaged cochlea and stimulates the auditory nerve with electrodes.

8.4 Speech impairment

Speech impairment is an impairment of speech or sound production, fluency, voice or language that significantly affects a child's educational performance or social, emotional or vocational development. † Management includes speech-language therapy and **augmentative and alternative communication (AAC)** aids such as communication boards and speech-generating devices.

8.5 Orthopaedic (locomotor) disability

Orthopaedic disability occurs when movements of the body are affected by disease, injury, absence or deformity of joints, bones or muscles, or by injury to the nervous system. **Locomotor disability** is a disability of bones, joints or muscles that substantially restricts movement of the limbs.

Devices for positioning and mobility: canes, walkers, crutches, wheelchairs, specialised exercise equipment, and specialised chairs, desks and tables for proper posture development. Prostheses and orthoses (Topic 7, Part 2) and brain-computer interfaces (Topic 9) extend this range of assistive devices.



Fig. 8.2 *Crutches, walker, wheelchair and postural seating.*

8.6 † Wheelchairs and functional electrical stimulation

- **Wheelchairs:** manual chairs are self-propelled or attendant-propelled; powered chairs use battery-driven motors controlled by joystick, chin, head or breath switches, or even a BCI; special types include sports, reclining and standing chairs. Correct seat size, cushion and posture support prevent pressure sores and deformity.
- **Functional electrical stimulation (FES):** low-level electrical pulses applied to paralysed muscles or nerves produce useful movement, for example correcting foot drop during walking or supporting hand grasp after spinal cord injury or stroke.

8.7 † Assistive technology at a glance

Impairment	Typical rehabilitation and assistive devices
Visual	Long cane, Braille display and embosser, screen reader, magnifier, talking devices
Hearing	Hearing aid, cochlear implant, assistive listening and visual-alert devices
Speech	Communication board, speech-generating device, eye-gaze communicator
Mobility	Manual or powered wheelchair, walker, crutches, prosthesis, orthosis, functional electrical stimulation
Cognitive	Reminders, simplified interfaces, monitoring and alarm systems

† Good rehabilitation design is user-centred, safe, comfortable, affordable, easy to maintain and adaptable as the person's needs change.

EXAM FOCUS

Short answer (2 marks)

1. Differentiate impairment, disability and handicap with one example each.
2. Distinguish conductive and sensorineural hearing loss.
3. What is augmentative and alternative communication (AAC)?
4. State the principle of functional electrical stimulation.
5. List two assistive devices for visual impairment.

Long answer (13 / 16 marks)

6. Describe the types of disability and the rehabilitation and assistive devices used for each.
7. Discuss wheelchairs, mobility aids and functional electrical stimulation in rehabilitation engineering.

TOPIC 9
Brain-Computer Interface (BCI) Fundamentals

A **Brain-Computer Interface (BCI)** allows direct communication between the brain and an external device, so a user can control the device through thought processes alone. BCIs were first developed for medical use and now extend to neuro-rehabilitation, control of assistive devices, gaming and more. They are especially valuable for people with motor disabilities, giving them a way to interact with the world and communicate.

9.1 Aim and working principle

The aim of a BCI is to:

- work from brain activity **without movement or motor activity**;
- record metabolic or electrical brain signals that are artefact-free;
- depend on the **user**, who must keep a close correlation between intention and the electrophysiological phenomena; and
- have the **BCI** translate those phenomena into device commands that accomplish the user's intent.

BCIs are modelled on the electrophysiology of the brain's neural network. When we decide, or even think of deciding, electrochemical signals fire between neurons at the synapses. Electrodes placed close to this activity detect the voltages and measure the frequency and intensity of each spike: "like a microphone, but listening to electrical activity instead of sound". The signals go to computer software for **neural decoding**, where machine-learning and other AI algorithms turn complex brain-activity data into an estimate of the user's intention.

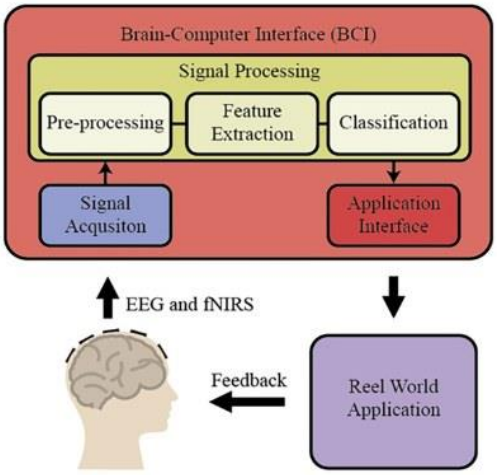


Fig. 9.1 *BCI: signal acquisition, pre-processing, feature extraction, classification, application interface and feedback.*

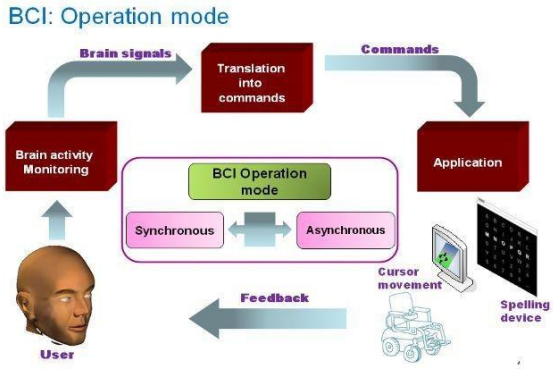


Fig. 9.2 *BCI operation: brain signals, translation into commands, application and feedback to the user.*

9.2 Components of a BCI

Stage	Function
Signal acquisition	Electrodes (on the scalp for EEG) detect the electrical signals generated by brain activity.
Signal processing	Acquired signals are filtered and amplified to remove noise and improve clarity (pre-processing).
Feature extraction	Relevant features that represent the user's intention are identified from the processed signals.

Stage	Function
Output device control	The interpreted signals (after classification) are translated into commands for external devices such as computers, wheelchairs or prosthetics.
† Feedback	The user sees or feels the result of the command and adapts, closing the loop.

9.3 Types of BCI

By mode of operation

Feature	Synchronous BCI	Asynchronous BCI
Operational mode	Works in preset time intervals or for specific tasks	Works continuously, interpreting brain signals at any time
User control	User must act within designated timeframes	User can control the system at any moment
Signal detection	Signal processed at fixed intervals	Signal continuously monitored for spontaneous activity
Response time	Limited to set periods, so response time may vary	Immediate response to detected brain activity
Applications	Controlled tasks such as spelling or gaming	Real-time uses such as robotic control
Accuracy	High	Variable

By invasiveness

Type	Electrode placement	Characteristics
Invasive	Electrodes implanted directly into the brain	High signal accuracy; used in medical settings for patients with severe motor impairment
Partially invasive	Electrodes on the surface of the brain (e.g. ECoG) without penetrating brain tissue	Balances accuracy with moderate invasiveness; often used in clinical research
Non-invasive	External EEG cap on the scalp	Lower-resolution signals but practical and widely applicable

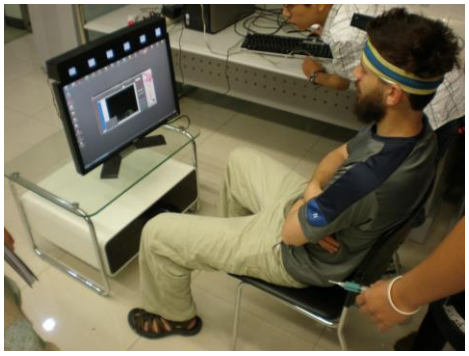


Fig. 9.3 *A user controlling a computer through a non-invasive EEG-based BCI.*

9.4 Signals used in BCI

Signal	Description †
Mu and alpha rhythms	Oscillations of about 8–12 Hz over motor and visual cortex; amplitude changes with movement or imagined movement.
ERD / ERS	Event-related desynchronisation (power decrease) and synchronisation (power increase) of mu/beta rhythms during motor imagery.
Slow cortical potentials (SCPs)	Slow voltage shifts of the cortex lasting seconds; users learn to make them positive or negative.
P300 (P3) wave	Positive peak about 300 ms after a rare or target stimulus; basis of many spellers.
Short-latency VEP	Visual evoked potential: brain's quick response to a visual stimulus.
SSVEP	Steady-state VEP: response at the flicker frequency of a visual target; allows fast target selection.
Individual neuron recordings	Spikes from single neurons using implanted microelectrodes (invasive).

9.5 Imaging and recording techniques

The choice of technique depends on safety, cost and ease of use.

Technique	Limitation / advantage
MRI, CT	Give only anatomical data
ECoG	Highly invasive surgery
SPECT, PET	Radiation exposure
MEG, fMRI	Extremely expensive
fNIRS	Currently expensive and still in its infancy
EEG	**Safe, easy, needs no medical expertise**, hence the most widely used for BCI

9.6 Applications

The near-term goal is to give back abilities to people who have lost them; in the long term BCIs may add a further level of brain function.

- **Medical and assistive:** robotic limbs and wheelchairs, wireless headsets, spellers, smartphone and smart-home interfaces, drones.
- **Other fields:** gaming and entertainment (hands-free control, VR/AR); smart home and IoT; military and defence (drone control, stress management); education (focus monitoring); workplace (workload and fatigue tracking); art (brain-controlled music); sports (mental training); space exploration (stress monitoring, hands-free control).

9.7 Challenges and advancements

Challenges	Advancements
• **Signal stability and reliability:** signals fluctuate with fatigue, attention and health • **Scalability** to more users and applications • **Real-time processing:** low latency is essential but demanding • **Ethical and legal issues:** privacy, consent and misuse of neural data • **Integrating neural data** from EEG, fMRI and others • **Long-term implant viability** and biocompatibility • **User adaptation:** users find interfaces hard to learn	• **AI integration:** machine learning and deep learning improve signal interpretation • **Non-invasive solutions:** better EEG and fNIRS make BCIs practical for daily use • **Wearable BCIs:** compact, user-friendly headsets • **Neuro-enhanced reality:** controlling AR and VR directly with thoughts

EXAM FOCUS

Short answer (2 marks)

1. What is a brain-computer interface?
2. Distinguish synchronous and asynchronous BCIs.
3. Define P300 and SSVEP signals.
4. Why is EEG the most widely used technique for BCI?
5. List two challenges of BCI systems.

Long answer (13 / 16 marks)

6. Explain the components of a BCI with a block diagram.
7. Discuss the types of BCI by invasiveness and the signals and imaging techniques used.
8. Describe the applications, challenges and recent advancements of BCI.

TOPIC 10
AI-Assisted Medical Devices

Artificial intelligence (AI) is moving medical devices from passive tools to **active, learning partners**. Instead of one-size-fits-all devices designed for population averages, AI lets interventions be tailored to each patient's genetics, environment and real-time physiological data, the "**N = 1**" approach to hyper-personalised care. The lecture material is based on a systematic review of more than 100 peer-reviewed studies, industry analyses and regulatory advisories (2016–2023) and reports a market growing from **US$15.1 billion (2022) to US$187.95 billion (2030)**, about 37% compound annual growth.



Fig. 10.1 *From generic to hyper-personalised devices, and projected market growth.*

10.1 How AI devices work: sense, comprehend, act, learn

An AI-assisted device follows a loop: **sense** (collect genomic, biometric and real-time physiological data), **comprehend** (find hidden patterns with complex algorithms), **act** (adjust treatment or generate clinical decisions) and **learn** (refine accuracy from new data).

- **Supervised learning:** trained on labelled data sets, e.g. diagnosing disease from pre-diagnosed X-ray databases.
- **Unsupervised learning:** finds hidden patterns in unlabelled data, e.g. patient subgroups in genomic studies.
- **Deep learning:** multi-layer neural networks (CNNs, 1D-CNNs) that analyse complex data such as images and biosignals, and can detect subtle anomalies in CT scans that humans miss.

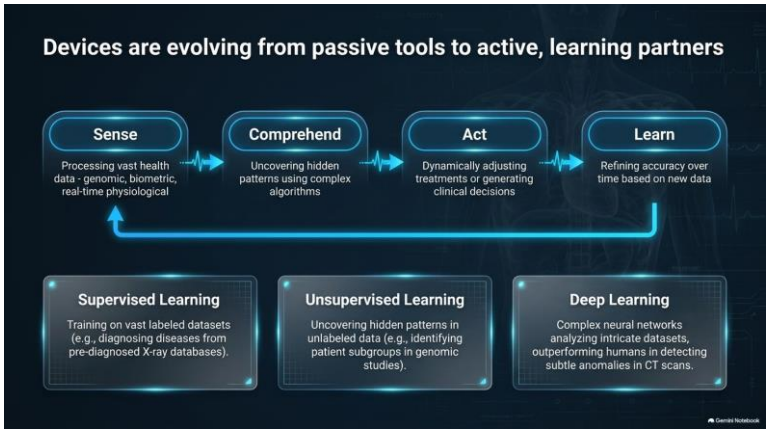


Fig. 10.2 *Sense–comprehend–act–learn loop and the main learning methods.*

10.2 Diagnostics: deep neural networks

Deep networks analyse medical images faster and often as accurately as experts. About **76% (777 of 1016)** of FDA-approved AI medical devices are in **radiology**. Reported examples:

- **Lung disease:** multiclass chest X-ray diagnosis (fibrosis, opacity, tuberculosis, viral pneumonia, COVID-19) reached **98.88% accuracy**; CT-lungNET classified small pulmonary nodules with AUROC 0.85 against 0.82 for AlexNet.
- **Breast cancer:** a deep CNN achieved an **AUC of 0.895**, as accurate as experienced radiologists; a hybrid AI + radiologist model did better than either.
- **Cardiac:** ECG classifiers (MobileNetV2, VGG16) reached 0.95 accuracy, and 0.94 and 0.90 when run on a Raspberry Pi embedded system.
- **Workflow:** AI automation could reduce diagnostic delays by up to 50%.

10.3 Smart therapeutics: closed-loop systems

In a closed loop the device **monitors** a signal, **predicts** what will happen and **adjusts** therapy automatically.

- **Smart insulin management:** continuous glucose monitors feed AI prediction algorithms that adjust insulin dose; smart insulin pens recognise the injection site and detect lipodystrophy with over 95% accuracy (one-class SVM).
- **Cardiac rhythm devices:** pacemakers adjust function from real-time physiological signals; CNNs predicted the risk of pacemaker-induced cardiomyopathy with about 75% accuracy before the implant procedure.

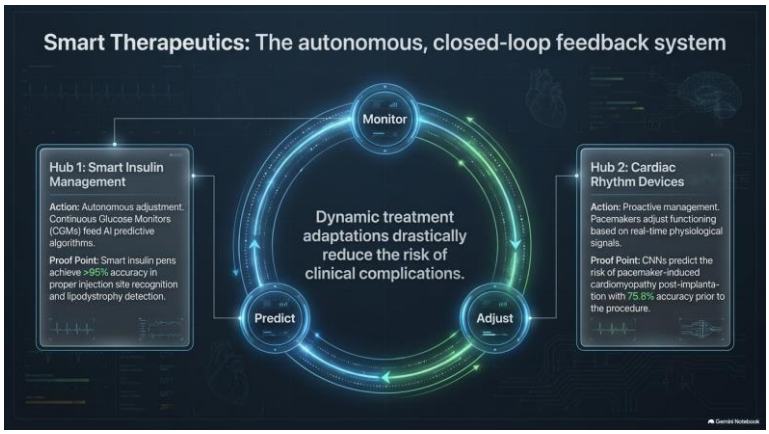


Fig. 10.3 *Closed-loop feedback: monitor, predict and adjust.*

10.4 Wearables and continuous telemetry

Wearables move care from reactive to continuous monitoring by sensing interstitial fluid, tears, saliva and sweat. The **GlucoNet** deep network estimates blood glucose non-invasively with a mean absolute percentage error (MAPE) of **17.8%**, with all predictions in clinically acceptable zones A and B of the Clarke error grid. Gradient-boosting models on an electronic multi-dose inhaler predicted **asthma exacerbations up to 5 days in advance** (ROC AUC 0.83).

10.5 Prosthetics and implants

AI turns raw data into adaptive anatomy. Machine-learning pipelines convert **CT scans** into patient-specific 3D models (classify bone slices, detect the knee region, segment femur and tibia, fit statistical shape models) for bespoke knee implants, cutting manual processing time by more than 75%. In rehabilitation, **surface EMG with a 1D-CNN** recognised hand gestures with **90.89% accuracy** in a stroke-rehabilitation glove, adapting to physiological changes over time. This links directly to myoelectric prostheses (Topic 7, Part 2) and BCI decoding (Topic 9).

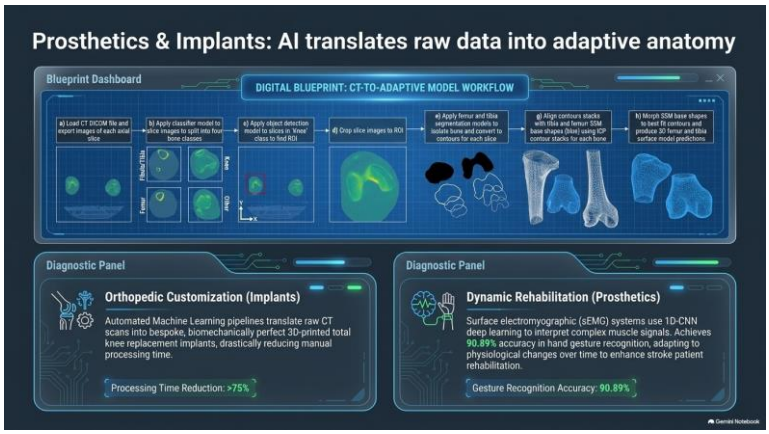


Fig. 10.4 *CT-to-adaptive-model workflow for implants and sEMG gesture recognition for prosthetics.*

10.6 Synthesis matrix

Device class	Primary input	Dominant AI method	Accuracy benchmark	Core value
Diagnostic	Medical images	Deep CNNs	Up to 98.88% in multiclass disease	Seeing the invisible
Therapeutic	Continuous biomarkers	Predictive ML algorithms	Over 95% injection-site recognition	Closed-loop adaptation
Wearable	Real-time telemetry	1D-CNNs and gradient boosting	Predicts events up to 5 days early	Proactive management
Prosthetic	CT scans and muscle signals	sEMG interpretation and 3D mapping	90.89% gesture recognition	Bespoke biomechanics

10.7 Case studies from the literature

Device	AI technique	Application	Reported outcome
Smart insulin pen	One-class SVM (machine learning)	Injection-site recognition, lipodystrophy detection	Over 95% accuracy
Insulin pump (type-1 diabetes)	AI predictive algorithms	Automatic insulin dosing, glucose prediction	Reports critical conditions to the care centre and keeps a data timeline
Wearable rehabilitation glove	1D-CNN, InceptionTime on sEMG	Hand rehabilitation after stroke	90.89% gesture-recognition accuracy
Lower-limb radiograph tool	U-Net CNN (LAMA)	Alignment and angles before and after knee arthroplasty	Good agreement with experts (ICC 0.78–1.00); twice as fast
Chest X-ray diagnostic tool	CNN	Multiclass lung-disease diagnosis	Accuracy 98.88%, AUC 0.9939
Wearable glucose monitor (IoMT)	GlucoNet deep neural network	Non-invasive glucose estimation	MAPE 17.8%; all readings in Clarke zones A and B
Electronic multi-dose inhaler	Gradient-boosting trees	Predicting asthma exacerbations	ROC AUC 0.83; up to 5 days early

Source: case-study table in the lecture slides (J Med Internet Res 2026; 28: e72410).

10.8 Barriers to clinical deployment

- **Technical:** data quality, data silos and interoperability with legacy hardware and electronic health records; the "black-box" problem of interpreting algorithms.
- **Ethical:** patient privacy and data security; algorithms trained on non-representative data can perpetuate inequities and perform differently across patient groups.
- **Regulatory:** lack of standard validation protocols; regulators struggle to keep pace with self-updating models; need for post-market surveillance and global harmonisation. Cybersecurity and patient consent are mandatory.

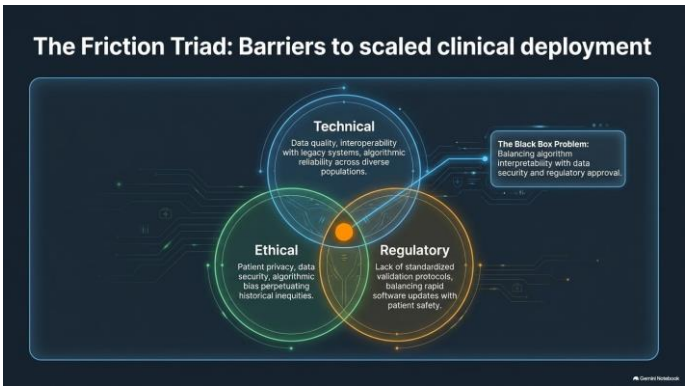


Fig. 10.5 *The friction triad: technical, ethical and regulatory barriers.*

10.9 Horizon technologies and outlook

The lecture projects that **quantum computing** could speed complex AI processing (10–20 times for AI-driven diagnosis) and **blockchain** could make health-data sharing tamper-proof (over 30% fewer security breaches). The vision for 2030 is that AI-assisted devices will **not replace the clinician but arm them with precision**, and that portable AI diagnostics and adaptive wearables will help close global health disparities.

10.10 Key terms

Term	Meaning
CNN / 1D-CNN	Convolutional neural network; the 1D form processes time signals such as ECG or sEMG
SVM	Support vector machine; a supervised classifier (one-class SVM detects departures from a normal pattern)
AUC / AUROC	Area under the ROC curve; 1.0 is perfect and 0.5 is chance
MAPE	Mean absolute percentage error between predicted and true values
sEMG	Surface electromyography: muscle electrical activity recorded from the skin
IoMT	Internet of Medical Things: connected medical devices and sensors

EXAM FOCUS

Short answer (2 marks)

1. Explain the sense–comprehend–act–learn loop of an AI-assisted device.
2. Differentiate supervised and unsupervised learning.
3. What is a closed-loop therapeutic system? Give one example.
4. List the technical, ethical and regulatory barriers to AI-assisted devices.
5. Define AUC and MAPE.

Long answer (13 / 16 marks)

6. Discuss the role of AI in diagnostic and therapeutic medical devices with examples.
7. Explain how AI is used in wearables, prosthetics and implants, and discuss the barriers to clinical deployment.