Prerequisites for digital modeling and quantification of altered upper extremity movement patterns after stroke

based on the Fugl-Meyer Assessment (FMA) scale, within a customized classification framework

STRATIF-AI *project* · Part I of II

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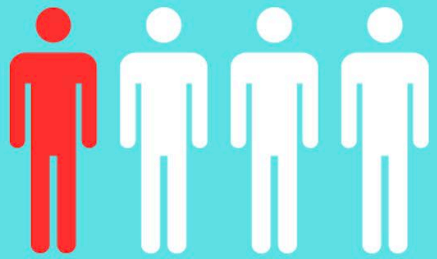
Part I

Clinical Background

***Key** notions*: *Stroke · Motor Deficit · Recovery/Rehabilitation · FMA scale · Digital Twin/ Avatar technology · Virtual coaching · Telerehabilitation · Continuum stratification/ of care*

Stroke — Epidemiology & Motor Consequences

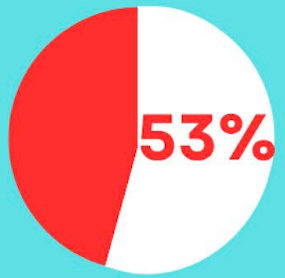
Global burden and upper extremity impact



¼ people have a stroke in their lifetime

12M new strokes every year

94M people living with the effects of stroke



of strokes occur in people **under 70**

~50% persistent upper limb impairment

#3 ?

cause of acquired death & neurological disability **GLOBALLY***

**GBD 2021 / WSO Fact Sheet 2024/2025 (*https://journals.sagepub.com/doi/10.1177/17474930241308142)

International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10)-WHO Version for ;2019-covid-expanded

Chapter IX
Diseases of the circulatory system
(I00-I99)

(https://icd.who.int/browse10/2019/en#/I60-I69)

Cerebrovascular diseases
(I60-I69)

Incl.: with mention of hypertension (conditions in I10 and I15.-)

Use additional code, if desired, to identify presence of hypertension.

Excl.: transient cerebral ischaemic attacks and related syndromes (G45.-)
traumatic intracranial haemorrhage (S06.-)
vascular dementia (F01.-)

I60 Subarachnoid haemorrhage
Excl.: sequelae of subarachnoid haemorrhage (I69.0)

- **I60.0 Subarachnoid haemorrhage from carotid siphon and bifurcation**
- **I60.1 Subarachnoid haemorrhage from middle cerebral artery**
- **I60.2 Subarachnoid haemorrhage from anterior communicating artery**
- **I60.3 Subarachnoid haemorrhage from posterior communicating artery**
- **I60.4 Subarachnoid haemorrhage from basilar artery**
- **I60.5 Subarachnoid haemorrhage from vertebral artery**
- **I60.6 Subarachnoid haemorrhage from other intracranial arteries**
  Multiple involvement of intracranial arteries
- **I60.7 Subarachnoid haemorrhage from intracranial artery, unspecified**
  Ruptured (congenital) berry aneurysm NOS
  Subarachnoid haemorrhage from: • cerebral • communicating — artery NOS
- **I60.8 Other subarachnoid haemorrhage**
  Meningeal haemorrhage
  Rupture of cerebral arteriovenous malformation
- **I60.9 Subarachnoid haemorrhage, unspecified**

I61 Intracerebral haemorrhage
Excl.: sequelae of intracerebral haemorrhage (I69.1)

- **I61.0 Intracerebral haemorrhage in hemisphere, subcortica**
  Deep intracerebral haemorrhage
- **I61.1 Intracerebral haemorrhage in hemisphere, cortical**
  Cerebral lobe haemorrhage
  Superficial intracerebral haemorrhage
- **I61.2 Intracerebral haemorrhage in hemisphere, unspecifie**
- **I61.3 Intracerebral haemorrhage in brain stem**
- **I61.4 Intracerebral haemorrhage in cerebellum**
- **I61.5 Intracerebral haemorrhage, intraventricular**
- **I61.6 Intracerebral haemorrhage, multiple localized**
- **I61.8 Other intracerebral haemorrhage**
- **I61.9 Intracerebral haemorrhage, unspecified**

I62 Other nontraumatic intracranial haemorrhage
Excl.: sequelae of intracranial haemorrhage (I69.2)

- **I62.0 Nontraumatic subdural haemorrhage**
- **I62.1 Nontraumatic extradural haemorrhage**
  Nontraumatic epidural haemorrhage
- **I62.9 Intracranial haemorrhage (nontraumatic), unspecified**

? "… is the main cause of death and the most common cause of acquired physical disability worldwide"*

* Haupt M, Gerner ST, Bähr M, Doeppner TR. Neuroprotective Strategies for Ischemic Stroke-Future Perspectives. Int J Mol Sci. 2023 Feb 22;24(5):4634. doi: 10.3390/ijms24054334. PMID: 36901765; PMCID: PMC10002358.

CVA has a marked tendency to generate "residual" DISABILITY*, i. e. "… almost two-thirds of STROKE survivors leave hospital with a DISABILITY"**

* Ropper A.H., Samuels M.A., Klein J.P. (Eds.) Cerebrovascular Diseases (Chapter 34). In: Adams and Victor's: Principles of Neurology.Tenth Edition.USA: Mc Graw Hill Education, 2014

** Veerbeek J M, Verheyden G. Stroke. In: Lennon S,

I63 Cerebral infarction
Incl.: occlusion and stenosis of cerebral and precerebral arteries (including truncus brachiocephalicus), resulting in cerebral infarction
Excl.: sequelae of cerebral infarction (I69.3)

- **I63.0 Cerebral infarction due to thrombosis of precerebral arteries**
- **I63.1 Cerebral infarction due to embolism of precerebral arteries**
- **I63.2 Cerebral infarction due to unspecified occlusion or stenosis of precerebral arteries**
- **I63.3 Cerebral infarction due to thrombosis of cerebral arteries**
- **I63.4 Cerebral infarction due to embolism of cerebral arteries**
- **I63.5 Cerebral infarction due to unspecified occlusion or stenosis of cerebral arteries**
- **I63.6 Cerebral infarction due to cerebral venous thrombosis, nonpyogenic**
- **I63.8 Other cerebral infarction**
- **I63.9 Cerebral infarction, unspecified**

I64 Stroke, not specified as haemorrhage or infarction
Incl.: Cerebrovascular accident NOS
Excl.: sequelae of stroke (I69.4)

I65 Occlusion and stenosis of precerebral arteries, not resulting in cerebral infarction
Incl.: embolism, narrowing, obstruction (complete)(partial), thrombosis — of basilar, carotid or vertebral arteries, not resulting in cerebral infarction
Excl.: when causing cerebral infarction (I63.-)

- **I65.0 Occlusion and stenosis of vertebral artery**
- **I65.1 Occlusion and stenosis of basilar artery**
- **I65.2 Occlusion and stenosis of carotid artery**
- **I65.3 Occlusion and stenosis of multiple and bilateral precerebral arteries**
- **I65.8 Occlusion and stenosis of other precerebral artery**
- **I65.9 Occlusion and stenosis of unspecified precerebral artery**
  Precerebral artery NOS

I66 Occlusion and stenosis of cerebral arteries, not resulting in cerebral infarction
Incl.: embolism, narrowing, obstruction (complete)(partial), thrombosis — of middle, anterior and posterior cerebral arteries, and cerebellar arteries, not resulting in cerebral infarction
Excl.: when causing cerebral infarction (I63.-)

- **I66.0 Occlusion and stenosis of middle cerebral artery**
- **I66.1 Occlusion and stenosis of anterior cerebral artery**
- **I66.2 Occlusion and stenosis of posterior cerebral artery**
- **I66.3 Occlusion and stenosis of cerebellar arteries**
- **I66.4 Occlusion and stenosis of multiple and bilateral cerebral arteries**
- **I66.8 Occlusion and stenosis of other cerebral artery**
  Occlusion and stenosis of perforating arteries
- **I66.9 Occlusion and stenosis of unspecified cerebral artery**

I67 Other cerebrovascular diseases
Excl.: sequelae of the listed conditions (I69.8)

- **I67.0 Dissection of cerebral arteries, nonruptured**
  Excl.: ruptured cerebral arteries (I60.7)
- **I67.1 Cerebral aneurysm, nonruptured**
  Cerebral: • aneurysm NOS • arteriovenous fistula, acquired
  Excl.: congenital cerebral aneurysm, nonruptured (Q28.-); ruptured cerebral aneurysm (I60.-)
- **I67.2 Cerebral atherosclerosis**
  Atheroma of cerebral arteries
- **I67.3 Progressive vascular leukoencephalopathy**
  Binswanger disease
  Excl.: subcortical vascular dementia (F01.2)
- **I67.4 Hypertensive encephalopathy**
- **I67.5 Moyamoya disease**
- **I67.6 Nonpyogenic thrombosis of intracranial venous system**
- **I67.7 Cerebral arteritis, not elsewhere classified**
- **I67.8 Other cerebrovascular diseases**
- **I67.9 Cerebrovascular disease, unspecified**

I68* Cerebrovascular disorders in diseases classified elsewhere

- **I68.0* Cerebral amyloid angiopathy (E85.-†)**
- **I68.1* Cerebral arteritis in infectious and parasitic diseases classified elsewhere**
  Cerebral arteritis: • bacterial (A52.0†) • syphilitic (A52.0†) • tuberculous (A18.8†)
- **I68.2* Cerebral arteritis in other diseases classified elsewhere**
  Cerebral arteritis in systemic lupus erythematosus (M32.1†)
- **I68.8* Other cerebrovascular disorders in diseases classified elsewhere**
  Uraemic apoplexia in chronic kidney disease (N18.5†)

I69 Sequelae of cerebrovascular disease
Note: Category I69 is to be used to indicate conditions in I60-I67.1 and I67.4-I67.9 as the cause of sequelae, themselves classified elsewhere. The "sequelae" include conditions specified as such or as late effects, or those present one year or more after onset of the causal condition.
Not to be used for chronic cerebrovascular disease. Code these to I60-I67.

- **I69.0 Sequelae of subarachnoid haemorrhage**
- **I69.1 Sequelae of intracerebral haemorrhage**
- **I69.2 Sequelae of other nontraumatic intracranial haemorrhage**
- **I69.3 Sequelae of cerebral infarction**
- **I69.4 Sequelae of stroke, not specified as haemorrhage or infarction**
- **I69.8 Sequelae of other and unspecified cerebrovascular diseases**

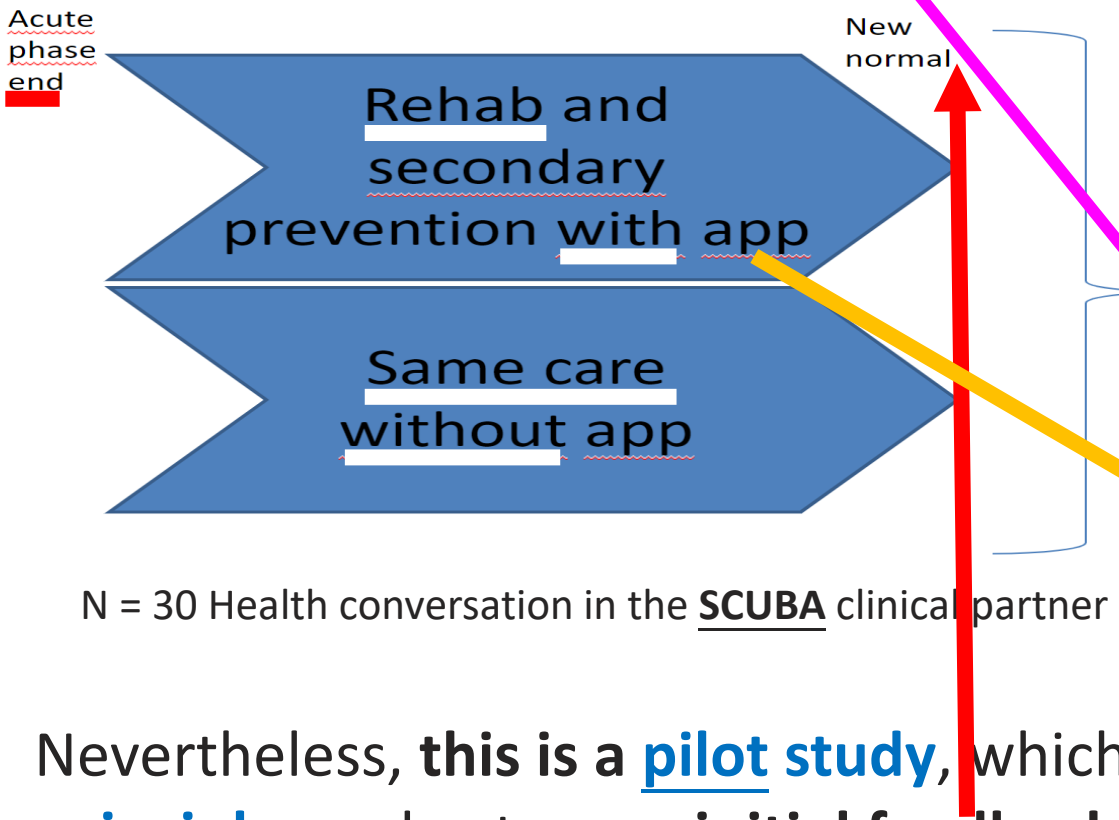
"Synonims" for Ischemic STROKE: "Brain attack"* "Cerebrovascular accident"* (CVA)** (Cerebral infarction/ ischemia)*** – respectively, for Hemorrhagic STROKE: "('spontaneous')Intra-cerebral Hemorrhage"**

* Stein J – Stroke (Chpt. 159, in: Frontera W.R., Silver J., Rizzo T.D., Jr. – Eds. – Essentials of Physica Medicine and Rehabilitation. Musculoskeletal Disorders, Pain, and Rehabilitation. Fourth Edition, Elsevier, Philadelphia, USA, 201

** Ropper A.H., Samuels M.A., Klein J.P. (Eds.) – Adams and Victor's: Principles of Neurology. Tenth Edition (Chpt. 34). Mc Graw Hill Education Medical, 2014. New York, Chicago, San Francisco, Athens don, Madrid, Mexico City, Milan, new Delhi, Singapore, Sydney, Toront

*** Gaillard F, Hacking C, Sharma R, et al. Ischemic stroke. Reference article, Radiopaedia.org (Accessed on 07 Jun 2023) https://doi.org/10.53347/rID-13437
DOI: https://doi.org/10.53347/rID-13437. https://radiopaedia.org/articles/ischaemic-stroke

Overview of Clinical study 6: an proof-of-principle study



Differences in understanding, motivation, behavior, outcome

In other words, **they will use the app to better understand their medical situation, and to set personal** (*just as they do in such otherwise*).

N = 30 Health conversation in the **SCUBA** clinical partner

Nevertheless, **this is a pilot study**, which just **will show proof-of-principle**, and get some **initial feedback**. It will, however, **lay the basis for a bigger study, to be done after the end of this project**.

The **UK FIM+FAM (Functional Assessment Measure)** – Developed by the UK FIM+FAM Users Group Version 2.2 Modified 23.10.10/12 Updated scoring manual to align with the training manual from Australasian Rehabilitation Outcomes Centre (*Turner-Stoke L. – https://www.kcl.ac.uk/nmpc/assets/rehab/fimfam-manual.pdf; **https://www.kcl.ac.uk/nmpc/assets/rehab/part-1-fimfam-training-general.pdf) – **shall be unitarily used within the Clinical Study 6 of our STRATIF-AI project Consortium**

Self-care	1. Eating
	2. *Swallowing
	3. Grooming
	4. Bath/Shower
	5. Dressing Upper Body
	6. Dressing Lower Body
	7. Toileting
Bowel and Bladder	8. Bladder Management
	9. Bowel Management
Mobility	10. Transfers: Bed/Chair/Wheelchair
	11. Transfers: Toilet
	12 Transfers: Tub/Shower
	13. *Transfers: Car
	14. Locomotion: Walking/wheelchair
	15. Locomotion: Stairs
	16. *Community Mobility
Communication	17. Comprehension
	18. Expression
	19.*Reading
	20. *Writing
	21. *Speech Intelligibility
Psychosocial	22. Social Interaction
	23. *Emotional Status
	24. *Adjustment to Limitation
	25. *Use of Leisure Time
Cognition	26. Problem Solving
	27. Memory
	28.*Orientation
	29. *Concentration
	30. *Safety Awareness
	Calculating Sub Scale Scores
Impairment set	Neurological Impairment Categories

EXTENDED ADL	Introduction to Extended ADL
	Meal Preparation
	Laundry
	Housework
	Shopping
	Home Finances
	Work/ education

* FAM items

"**FAM items** are **rated** on **the same 7-level scale as the FIM items** although the scaling structure of the FIM does not always lend itself to the more abstract nature of the FAM items"

As well as **a specialized questionnaire** (targeting **2 aspects**: **the impact on the patients in the study group of interacting with the AI-capable avatar – "Digital Twin" – and the functioning of the hardware and software system used within the Clinical Studies**).

STRATIF-AI has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101080875

Post-Stroke Motor Deficit — Clinical Picture

Spasticity · movement synergies · recovery stages

Spasticity

Velocity-dependent increase in muscle tone *

Results from loss of supraspinal inhibition → hyperexcitability of stretch reflex.

Limits selective motor control and functional use of the limb.

Flexor / Extensor Synergies

Stereotyped mass movement patterns that **dominate early recovery** (Brunnstrom stages).

Still: **Severity of synergy ~ severity of deficit**

Recovery Stages

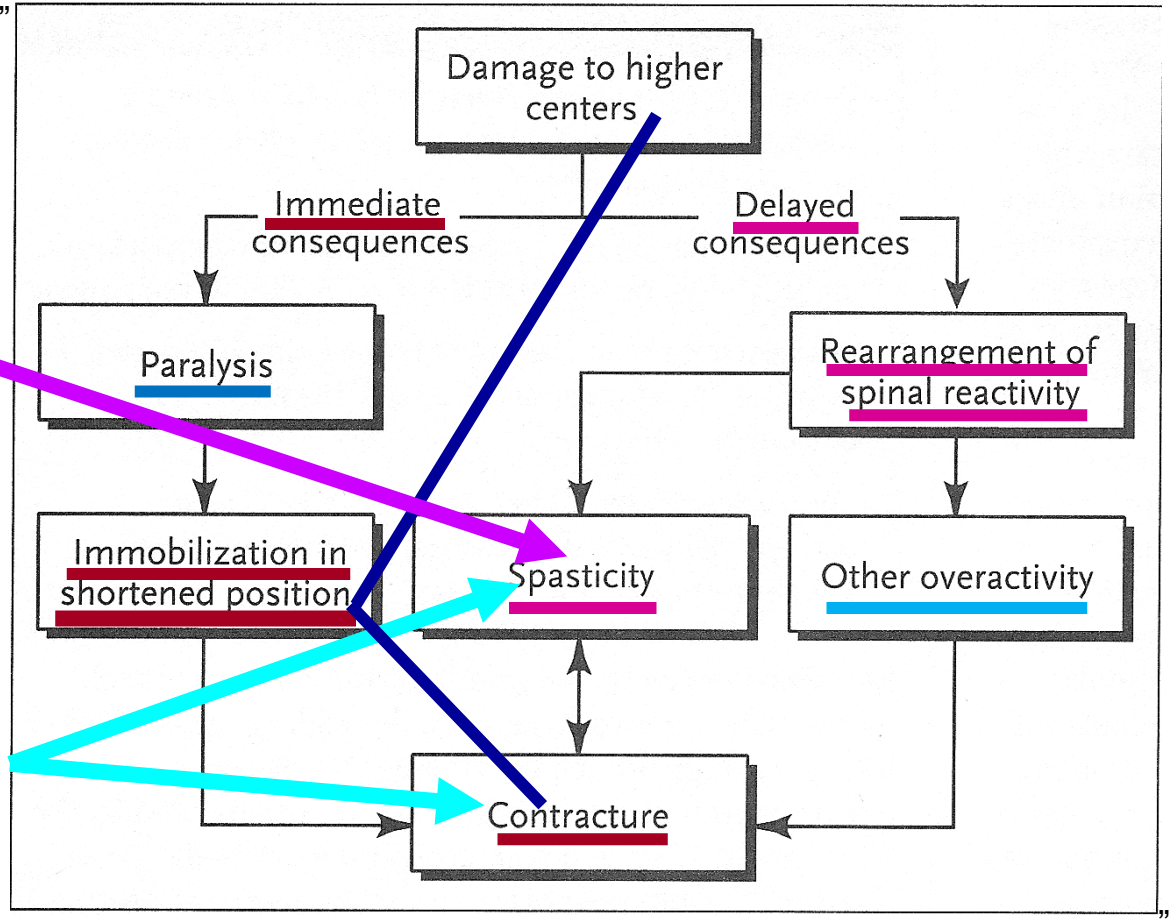
Twitchell & Brunnstrom**,***:

1. Flaccidity
2. Spasticity appears
3. Synergy peaks
4. Voluntary separation begins
5. Selective control
6. Near-normal

FMA directly maps onto this recovery hierarchy — each section tests a specific stage

Selective motor control (FMA scores **2**) = **goal of an effective motor rehabilitation** – *see further related* ***Annex***

*Lance JW. *Spasticity: Disordered Motor Control.* Year Book Medical Publishers; 1980.
**Twitchell TE. *Brain.* 1951;74(4):443-480.
***Brunnstrom S. J Am Phys Ther Assoc. 1966;46(4):357-375.

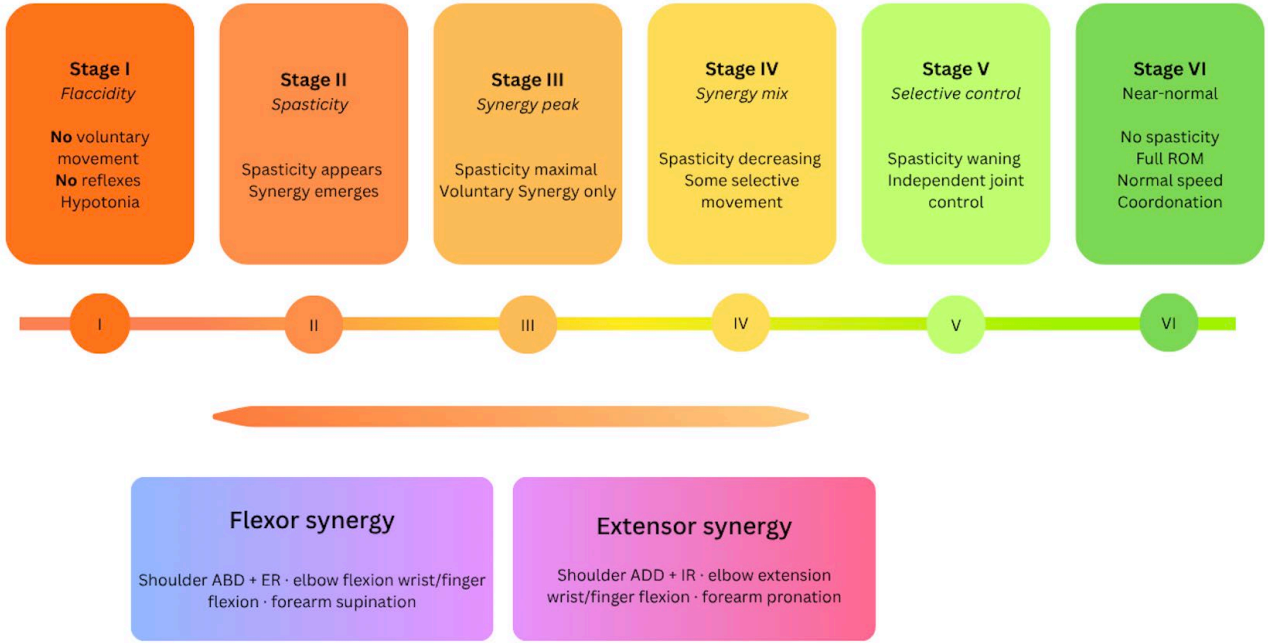


Pathophysiology of Impairment After a Central Nervous System Lesion" (*by*: *)

* Mayer NH, Simpson DM – Spasticity: Etiology, Evaluation, Management and the role of Botulinum Toxin. We move, 2002

Twitchell (1951)* & Brunnstrom (1966)**

Spasticity · movement synergies · recovery stages



*Twitchell TE. *Brain.* 1951;74(4):443-480.

**Brunnstrom S. J Am Phys Ther Assoc. 1966;46(4):357-375.

Fugl-Meyer Assessment — Global Reach & Clinical Adoption

FUGL-MEYER ASSESSMENT **ID:**
UPPER EXTREMITY (FMA-UE) **Date:**
Assessment of sensorimotor function **Examiner:**

Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S: The post-stroke hemiplegic patient. A method for evaluation of physical performance. Scand J Rehabil Med 1975, 7:13-31.

A. UPPER EXTREMITY, sitting position

I. Reflex activity

	none	can be elicited
Flexors: biceps and finger flexors (at least one)	0	2
Extensors: triceps	0	2
Subtotal I (max 4)		

II. Volitional movement within synergies, without gravitational help

			none	partial	full
Flexor synergy: Hand from contralateral knee to ipsilateral ear. From extensor synergy (shoulder adduction/ internal rotation, elbow extension, forearm pronation) to flexor synergy (shoulder abduction/ external rotation, elbow flexion, forearm supination). **Extensor synergy:** Hand from ipsilateral ear to the contralateral knee	Shoulder	retraction	0	1	2
		elevation	0	1	2
		abduction (90°)	0	1	2
		external rotation	0	1	2
	Elbow	flexion	0	1	2
	Forearm	supination	0	1	2
	Shoulder	adduction/internal rotation	0	1	2
	Elbow	extension	0	1	2
	Forearm	pronation	0	1	2
Subtotal II (max 18)					

III. Volitional movement mixing synergies, without compensation

		none	partial	full
Hand to lumbar spine hand on lap	cannot perform or hand in front of ant-sup iliac spine hand behind ant-sup iliac spine (without compensation) hand to lumbar spine (without compensation)	0	1	2
Shoulder flexion 0°- 90° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion abduction or elbow flexion during movement flexion 90°, no shoulder abduction or elbow flexion	0	1	2
Pronation-supination elbow at 90°, shoulder at 0°	no pronation/supination, starting position impossible limited pronation/supination, maintains starting position full pronation/supination, maintains starting position	0	1	2
Subtotal III (max 6)				

IV. Volitional movement with little or no synergy

		none	partial	full
Shoulder abduction 0 - 90° elbow at 0° forearm neutral	immediate supination or elbow flexion supination or elbow flexion during movement abduction 90°, maintains extension and pronation	0	1	2
Shoulder flexion 90° - 180° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion abduction or elbow flexion during movement flexion 180°, no shoulder abduction or elbow flexion	0	1	2
Pronation/supination elbow at 0° shoulder at about 30° flexion	no pronation/supination, starting position impossible limited pronation/supination, maintains start position full pronation/supination, maintains starting position	0	1	2
Subtotal IV (max 6)				

V. Normal reflex activity assessed only if full score of 6 points is achieved in part IV; compare with the unaffected side

		hyper	lively	normal
Biceps, triceps, finger flexors	2 of 3 reflexes markedly hyperactive 1 reflex markedly hyperactive or at least 2 reflexes lively maximum of 1 reflex lively, none hyperactive	0	1	2
Subtotal V (max 2)				

Total A (max 36)

B. WRIST support may be provided at the elbow to take or hold the starting position, no support at wrist, check the passive range of motion prior testing

		none	partial	full
Stability at 15° dorsiflexion elbow at 90°, forearm pronated shoulder at 0°	less than 15° active dorsiflexion dorsiflexion 15°, no resistance tolerated maintains dorsiflexion against resistance	0	1	2
Repeated dorsifexion / volar flexion elbow at 90°, forearm pronated shoulder at 0°, slight finger flexion	cannot perform volitionally limited active range of motion full active range of motion, smoothly	0	1	2
Stability at 15° dorsiflexion elbow at 0°, forearm pronated slight shoulder flexion/abduction	less than 15° active dorsiflexion dorsiflexion 15°, no resistance tolerated maintains dorsiflexion against resistance	0	1	2
Repeated dorsifexion / volar flexion elbow at 0°, forearm pronated slight shoulder flexion/abduction	cannot perform volitionally limited active range of motion full active range of motion, smoothly	0	1	2
Circumduction elbow at 90°, forearm pronated shoulder at 0°	cannot perform volitionally jerky movement or incomplete complete and smooth circumduction	0	1	2
Total B (max 10)				

C. HAND support may be provided at the elbow to keep 90° flexion, no support at the wrist, compare with unaffected hand, the objects are interposed, active grasp

		none	partial	full
Mass flexion from full active or passive extension		0	1	2
Mass extension from full active or passive flexion		0	1	2
GRASP				
a. Hook grasp flexion in PIP and DIP (digits II-V), extension in MCP II-V	cannot be performed can hold position but weak maintains position against resistance	0	1	2
b. Thumb adduction 1-st CMC, MCP, IP at 0°, scrap of paper between thumb and 2-nd MCP joint	cannot be performed can hold paper but not against tug can hold paper against a tug	0	1	2
c. Pincer grasp, opposition pulpa of the thumb against the pulpa of 2-nd finger, pencil, tug upward	cannot be performed can hold pencil but not against tug can hold pencil against a tug	0	1	2
d. Cylinder grasp cylinder shaped object (small can) tug upward, opposition of thumb and fingers	cannot be performed can hold cylinder but not against tug can hold cylinder against a tug	0	1	2
e. Spherical grasp fingers in abduction/flexion, thumb opposed, tennis ball, tug away	cannot be performed can hold ball but not against tug can hold ball against a tug	0	1	2
Total C (max 14)				

D. COORDINATION/SPEED, sitting, after one trial with both arms, eyes closed, tip of the index finger from knee to nose, 5 times as fast as possible

		marked	slight	none
Tremor		0	1	2
Dysmetria	pronounced or unsystematic slight and systematic no dysmetria	0	1	2
		≥ 6s	**2 - 5s**	**< 2s**
Time start and end with the hand on the knee	6 or more seconds slower than unaffected side 2-5 seconds slower than unaffected side less than 2 seconds difference	0	1	2
Total D (max 6)				

TOTAL A-D (max 66)

H. SENSATION, upper extremity
eyes closed, compared with the unaffected side

		anesthesia	hypoesthesia or dysesthesia	normal
Light touch	upper arm, forearm palmary surface of the hand	0 0	1 1	2 2
		less than 3/4 correct or absence	**3/4 correct or considerable difference**	**correct 100%, little or no difference**
Position small alterations in the position	shoulder elbow wrist thumb (IP-joint)	0 0 0 0	1 1 1 1	2 2 2 2
Total H (max12)				

I. PASSIVE JOINT MOTION, upper extremity,
sitting position, compare with the unaffected side

	only few degrees (less than 10° in shoulder)	decreased	normal
Shoulder			
Flexion (0° - 180°)	0	1	2
Abduction (0°-90°)	0	1	2
External rotation	0	1	2
Internal rotation	0	1	2
Elbow			
Flexion	0	1	2
Extension	0	1	2
Forearm			
Pronation	0	1	2
Supination	0	1	2
Wrist			
Flexion	0	1	2
Extension	0	1	2
Fingers			
Flexion	0	1	2
Extension	0	1	2
Total (max 24)			

J. JOINT PAIN during passive motion, upper extremity

	pronounced pain during movement or very marked pain at the end of the movement	some pain	no pain
Shoulder			
Flexion (0° - 180°)	0	1	2
Abduction (0°-90°)	0	1	2
External rotation	0	1	2
Internal rotation	0	1	2
Elbow			
Flexion	0	1	2
Extension	0	1	2
Forearm			
Pronation	0	1	2
Supination	0	1	2
Wrist			
Flexion	0	1	2
Extension	0	1	2
Fingers			
Flexion	0	1	2
Extension	0	1	2
Total (max 24)			

A. UPPER EXTREMITY	/36
B. WRIST	/10
C. HAND	/14
D. COORDINATION / SPEED	/ 6
TOTAL A-D (motor function)	/66

H. SENSATION	/12
I. PASSIVE JOINT MOTION	/24
J. JOINT PAIN	/24

*https://www.gu.se/en/neuroscience-physiology/fugl-meyer-assessment

Impact on the Patient — ADL & Quality of Life

Upper extremity deficit beyond the neurological examination

Self-care

Dressing, grooming, eating — all require coordinated bilateral upper limb function.

Work & Leisure

Return to employment severely impacted. Hobbies and social participation restricted.

Psychological

Loss of independence → depression in 30-40% of stroke survivors. Reduced self-efficacy.*

Caregiver Burden

Persistent upper limb deficit increases dependence on caregivers and institutional care.

*The arm is the "forgotten limb" in stroke rehabilitation***

- only **18%** of those with severe UE paresis regain full function***
- early FMA-UE score is among the strongest predictors of long-term independence
- frequency and quality of assessment – linked to rehabilitation outcomes

*Hackett ML, Pickles K. Int J Stroke. 2014;9(8):1017-1025.
**Kwakkel G, et al. Restor Neurol Neurosci. 2003;21(3-4):69-83
***Jørgensen HS, et al. *Arch Phys Med Rehabil.* 1995;76(5):406-412.

The Fugl-Meyer Assessment (FMA)*

Gold standard for post-stroke motor function

Structure

Upper extremity:
33 items · max 66 pts

Lower extremity:
17 items · max 34 pts

Scoring

3-point ordinal scale:
0 = cannot perform
1 = partial performing
2 = full performing

Psychometrics

- Interclass Correlation Coefficient (ICC): 0.96-0.97**
- Minimal Detectable Change (MDC) =6.82 pts (for the UE)***
- Responsive to change
- Widely validated

Assessment hierarchy — mirrors Brunnstrom recovery:

1. Reflex activity
2. Within synergy
3. Mixing synergies
4. Little/no synergy
5. Wrist, hand
6. Coordination/speed

← Severity increases · Stages reflect neurological recovery →

**Fugl-Meyer AR et al. Scand J Rehabil Med. 1975;7(1):13-31.*
***Sanford J, et al. Phys Ther. 1993;73(7):447-454.*
*** Huynh BP, et al. Neurorehabil Neural Repair. 2023;37(8):545-553.

‘The **Fugl-Meyer Assessment** Scale (**FMA**):

- is an **exhaustive assay instrument of neuro-functional status** in **upper** (**UE**) and **lower** (**LE**), **B, A** (for us) **extremity**
- it takes ~ **30 minutes*** (?- o. n.)/**45 minutes****;
  all **tests within the scale** must be **performed according** to related, **specific guidelines****
- it assesses **reflex**, **tremor** and/or **dysmetria** *(if they exists)* and **volitional movements**; this **includes**:

”flexor **synergy**, extensor **synergy**, movement **combining synergies**, movement **out of synergy**, **wrist & hand** and **coordination/speed**”, and **grasping**’** **...**

* https://www.sralab.org/rehabilitation-measures/fugl-meyer-assessment-motor-recovery-after-stroke

** APTA (2011). Compendium of Instructions for Outcome Measures - StrokEDGE Taskforce. APTA Neurology – pp: 51, 55-67, 70-74

...

- it measures, as well, **sensory** (ligt touch and propriception) functions/impairments*

- overall, the **FMA maximum** – ***just mathematically*** – **possible score** is 226/212 **points** (based on the following **ordinal grading**: "**0**=cannot perform **1**=performs partially **2**=performs fully")**; effectively: 182/168

- it encompasses **five** evaluation **domains**: **motor** (**maximum 66** points in **UE** and **34** in **LE**) and **sensory** (**maximum 24** points), functions; **balance** (**maximum 14 points**), joint **range** of **motion** (**maximum 44** points) and respectively, **pain** (**maximum 44** points ...).** ***negative trend***

* APTA (2011). Compendium of Instruments for Outcome Measures - StrokEDGE Taskforce. APTA Neurology – pp: 51, 55-67, 70-74

** https://www.sralab.org/rehabilitation-measures/fugl-meyer-assessment-motor-recovery-after-stroke

...

The Fugl-Meyer Assessment — Global Reach & Romanian Translation Validated

22+ language versions · international standard · locally validated

Global Standard

- Published 1975
- Translated into 22+ languages
- Hosted & maintained by University of Gothenburg – its official administrators
- Protocols freely available – with the accept of its official administrators: the Gothenburg University, in Sweeden – for clinical & research use
- Languages include: Danish, Greek, Italian, Korean, Latvian, Norwegian, Persian, **Romanian**, Spanish, Ukrainian, Urdu, and more*

Romanian Translation Validated

- **Our group published the validated Romanian translation of the FMA-UE and FMA-LE in 2023**
- **Transcultural and semantic-linguistic adaptations + clinical validation**
- Published in Frontiers in Neurology
- Both UE and LE protocols available in Romanian (PDF)**

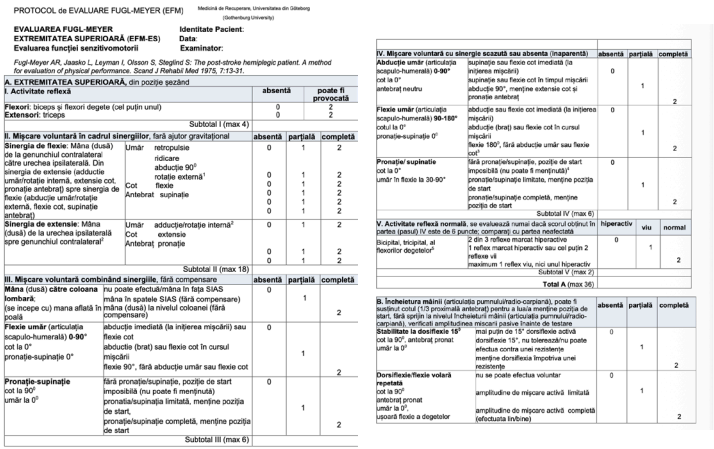
Relevance for STRATIF-AI

- Present work builds including on the 2023 Romanian FMA validation
- Methodology anchored in both international standards and local clinical practice
- **Our customized protocol is used as reference for movement inventory and scoring**

*University of Gothenburg FMA Registry: gu.se/fugl-meyer-assessment
**Onose G, et al. *Front Neurol.* 2023;13:1022546

Fugl-Meyer Assessment — Global Reach & Clinical Adoption

*Notably, a validated **Romanian translation** of the FMA-UE was published in 2023, confirming the scale's relevance within the local clinical and research community — and providing direct methodological grounding for the present work.*



PROTOCOL de EVALUARE FUGL-MEYER (EFM)

Medicină de Recuperare, Universitatea din Göteborg (Gothenburg University)

EVALUAREA FUGL-MEYER — **Identitate Pacient:**
EXTREMITATEA SUPERIOARĂ (EFM-ES) — **Data:**
Evaluarea funcției senzitivomotorii — **Examinator:**

Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S: The post-stroke hemiplegic patient. A method for evaluation of physical performance. Scand J Rehabil Med 1975, 7:13-31.

A. EXTREMITATEA SUPERIOARĂ, din poziție șezând

			absentă	poate fi provocată
I. Activitate reflexă				
Flexori: biceps și flexori degete (cel puțin unul)			0	2
Extensori: triceps			0	2
Subtotal I (max 4)				
II. Mișcare voluntară în cadrul sinergiilor, fără ajutor gravitațional			absentă	parțială	completă
Sinergia de flexie: Mâna (dusă) de la genunchiul contralateral/ către urechea ipsilaterală. Din sinergia de extensie (adducție umăr/rotație internă, extensie cot, pronație antebraț) spre sinergia de flexie (abducție umăr/rotație externă, flexie cot, supinație antebraț)	Umăr	retropulsie	0	1	2
		ridicare			
		abducție 90°	0	1	2
		rotație externă[1]	0	1	2
	Cot	flexie	0	1	2
	Antebraț	supinație	0	1	2
			0	1	2
Sinergia de extensie: Mâna (dusă) de la urechea ipsilaterală spre genunchiul contralateral[2]	Umăr	adducție/rotație internă[2]	0	1	2
	Cot	extensie			
	Antebraț	pronație			
			0	1	2
Subtotal II (max 18)					
III. Mișcare voluntară combinând sinergiile, fără compensare			absentă	parțială	completă
Mâna (dusă) către coloana lombară. (se încep cu) mana aflată în poziția inițială	nu poate efectua mâna în fața SIAS (fără compensare)		0		
	mâna în spatele SIAS (fără compensare)			1	
	mâna (dusă) la nivelul coloanei (fără compensare)				2
Flexie umăr (articulația scapulo-humerală) **0-90°** cot la 0° pronație-supinație 0°	abducție imediată (la inițierea mișcării) sau flexie cot		0		
	abducție (brat) sau flexie cot în cursul mișcării			1	
	flexie 90°, fără abducție umăr sau flexie cot				2
Pronație-supinație cot la 90° umăr la 0°	fără pronație/supinație, poziție de start imposibilă (nu poate fi menținută)		0		
	pronația/supinația limitată, menține poziția de start,			1	
	pronație/supinație completă, menține poziția de start				2
Subtotal III (max 6)					

IV. Mișcare voluntară cu sinergie scăzută sau absentă (inaparentă)			absentă	parțială	completă
Abducție umăr (articulația scapulo-humerală) **0-90°** cot la 0° antebraț neutru		supinație sau flexie cot în timpul mișcării inițiere mișcării)	0		
		abducție 90°, mențin extensie cot și pronație antebraț		1	2
Flexie umăr (articulația scapulo-humerală) **90-180°** cotul la 0° pronație-supinație 0°		abducție sau flexie cot imediată (la inițierea mișcării)	0		
		abducție (brat) sau flexie cot în cursul mișcării		1	
		flexie 180°, fără abducție umăr sau flexie cot			2
Pronație/ supinație cot la 0° umăr în flexie la 30-90°		fără pronație/supinație, poziție de start	0		
		imposibilă (nu poate fi menținută)[4]			
		pronație/supinație limitată, menține poziția de start		1	
		pronație/supinație completă, menține poziția de start			2
Subtotal IV (max 6)					
V. Activitate reflexă normală, se evaluează numai dacă scorul obținut în IV este de 6 puncte; comparați cu partea neafectată			hiperactiv	viu	normal
Bicipital, tricipital, al flexorilor degetelor[2]		2 din 3 reflexe marcat hiperactiv	0		
		1 reflex marcat hiperactiv sau cel puțin 2 reflexe vii		1	
		maximum 1 reflex viu, nici unul hiperactiv			2
Subtotal V (max 2)					
Total A (max 36)					

B. Încheietura mâinii (articulația pumnului/radio-carpiană), poate fi susținut cotul (1/3 proximală antebraț) pentru a lua/menține poziția de start, fără sprijin (a încheieturii mâinii (articulația pumnului/radio-carpiană), verificați amplitudinea mișcari pasive înainte de testare			absentă	parțială	completă
Stabilitate la dorsiflexie 15° cot la 90°, antebraț pronat, umăr la 0°		mai puțin de 15° dorsiflexie activă	0		
		dorsiflexie 15°, nu tolerează/nu poate efectua contra unei rezistențe		1	
		menține dorsiflexia împotriva unei rezistențe			2
Dorsiflexie/flexie volară repetată cot la 90° antebraț pronat umăr la 0°, ușoară flexie a degetelor		nu se poate efectua voluntar	0		
		amplitudine de mișcare activă limitată		1	
		amplitudine de mișcare activă completă (efectuata lin/ bine)			2

Stabilitate la dorsiflexie 15° cot la 0°, antebraț pronat ușoară flexie/abducție umăr		mai puțin de 15° dorsiflexie activă	0		
		dorsiflexie 15°, nu tolerează/nu poate efectua contra unei rezistențe		1	
		menține dorsiflexia împotriva unei rezistențe			2
Dorsiflexie/flexie volară repetată cot la 0°, antebraț pronat ușoară flexie/abducție umăr		nu se poate efectua voluntar	0		
		amplitudine de mișcare activă limitată		1	
		amplitudine de mișcare activă completă (efectuata lin/ bine)			2
Circumducție cot la 90°, antebraț pronat umăr la 0°		nu se poate efectua voluntar	0		
		mișcare nearmonioasa sau incompleta		1	
		circumducție completa, efectuata lin/bine			2
Total B (max 10)					

C. MÂNA, poate fi susținut cotul (1/3 proximală antebraț) pentru a menține 90° flexie, fără sprijin la nivelul încheieturii mâinii (articulația pumnului/radio-carpiană), comparați cu mana neafectata , se inlerpun obiecte pentru prehensiune/prindere activă			absentă	parțială	completă
Flexie globală/în bloc (a tuturor degetelor) din poziție de extensie completă activă sau pasivă (antebraț în poziție neutră)			0	1	2
Extensie globală/în bloc (a tuturor degetelor) din poziție de flexie completă activă sau pasivă (antebraț în poziția neutră)			0	1	2
PREHENSIUNE					
a. Prehensiune/prindere cârlig flexie în articulațiile interfalangiene proximale și distale (degetele II-V), extensie în articulațiile metacarpofalangiene II-V (antebraț în poziție neutră)		nu se poate efectua voluntar	0		
		se menține poziția impotriva unei rezistente, dar slab		1	
		se menține poziția impotriva unei rezistente			2
b. Adducție police prima articulație carpometacarpiană, metacarpofalangiană, interfalangiană la 0°, bucată de hârtie (introdusă) între police și o doua articulație metacarpofalangiană (antebraț în poziție semi-pronată)		nu se poate efectua voluntar	0		
		poate tine hartia si impotriva tragerii acesteia		1	
		poate tine hartia si impotriva tragerii acesteia			2

c. Pensa bidigitală, opoziția pulpa police/ui față de pulpa degetului 2, se trage în sus un creion (tinut de pedent între degetele respective) (antebraț în poziție neutră)		nu se poate efectua	0		
		poate (ine creionul, dar nu impotriva tragerii acestuia		1	
		poate (ine creionul și împotriva tragerii acestuia			2
d. Priza cilindrică (obiect de formă cilindrică (cană mică) trasă în sus (strâns police și degete – sfat în cozette cu degetele – respectiv poligito-palmară; antebraț în poziție neutră)		nu se poate efectua	0		
		poate tine cilindrul dar nu impotriva smulgerii acesteia		1	
		poate tine cilindrul și impotriva smulgerii acestuia			2
e. Prize sferică (degetele în abducție/flexie, policele în opoziție, mingie de tenis, trasă în afară (antebraț în poziție neutră)		nu se poate efectua	0		
		poate tine sfera dar nu impotriva tragerii acesteia		1	
		poate tine sfera și impotriva tragerii acesteia			2
Total C (max 14)					

Încheietura mâinii (articulația pumnului/radio-carpiană) police (articulația interfalangiană)			0	1	2
			0	1	2
Total H (max12)					

D. (DIS)COORDONARE/VITEZĂ, din poziție șezând, după o testare la atingerile membre superioare, ochi închiși, vârful indexului (depinsat) de la genunchiul ipsilateral la nas de 5 ori, cât mai rapid posibil			marcat	ușor	absent
Tremor			0	1	2
Dismetrie	pronunțată sau neisistematizată (neisistematizată)		0	1	
	ușoară și sistematizată (sistematizată)				2
	fără dismetrie				
		≥ 6s	**2.5s**	**< 2s**	
Timp începere și terminare cu mâna pe genunchi	cu 6 secunde sau mai mult, mai lent decat pe partea neafectată		0		
	cu 2-6 secunde mai lent decat pe partea neafectată			1	
	mai puțin de 2 secunde diferență				2
Total D (max 6)					

TOTAL A-D (max 66)				
H. SENSIBILITATE, extremitatea superioară, ochi închiși, comparați cu partea neafectată		**anestezie**	**hipoestezie sau disestezie**	**normal**
Atingere ușoară	brat, antebraț, fața palmară a mâinii	0	1	2
		0	1	2
		mai puțin de 3/4 sau absentă (senzibilitate)	**3/4 corectă sau diferență considerată**	**corectă100%, diferență mică sau fără diferență**
Poziție aferenți ușoare ale poziției	umăr	0	1	2
	cot	0	1	2

A. EXTREMITATEA SUPERIOARĂ	/36
B. Încheietura mâinii (articulația pumnului/radio-carpiană)	/10
C. MÂNA	/14
D. (DIS)COORDONARE/VITEZĂ	/6
TOTAL A-D (funcție motorie)	/66
H. SENSIBILITATE	/12
I. MOBILITATE ARTICULARĂ PASIVĂ	/24
J. DURERE ARTICULARĂ	/24

I. MOBILITATE ARTICULARĂ PASIVĂ, extremitatea superioară, (din poziție șezând), comparați cu partea neafectată		scăzută (între 10° – spre exp. în umăr – și val. norm. în artic. resp.)	normală	**J. DURERE ARTICULARĂ**, în timpul mișcării pasive, extremitatea superioară		
	doar câteva grade (mai puțin de 10° în umăr)			durere pronunțată în timpul mișcării sau foarte marcată la finalul mișcării	ușoară	fără durere
Umăr (articulația scapulo-humerală)						
Flexie (0° - 180°)	0	1	2	0	1	2
Abducție (0°-90°)	0	1	2	0	1	2
Rotație externă	0	1	2	0	1	2
Rotație internă	0	1	2	0	1	2
Cot						
Flexie	0	1	2	0	1	2
Extensie	0	1	2	0	1	2
Antebraț						
Pronație	0	1	2	0	1	2
Supinație	0	1	2	0	1	2
Degete						
Flexie	0	1	2	0	1	2
Extensie	0	1	2	0	1	2
Total (max 24)						

(Afferent to the FMA-Upper Extremity – UE), i. e.: Aferent la evaluarea Fugl-Meyer – extremitatea superioară:

1. abducție și rotație externă – articulația scapulo-humerală
2. poate fi susținut brațul pentru a lua/menține poziția de start
   - prezența doar a mișcărilor compensatorii în locul celor active se cuantifică/punctează cu 0 (exemple:
3. flexie antebraț și pronație, la flexia brațului/umăr 90-180°;
4. abducție și flexie cot la supinație)
5. mâna în pronație, degetele pacientului in semiflexie MCF și IF, sprijinite relaxat pe indexul și mediusul examinatorului, cand acesta își percută de jos în sus cu ciocanul de reflexe proprille degete, se poate obține o flexie a degetelor pacientului, aspect posibil normal

*Onose G, et al. Front Neurol. 2023;13:1022546.

frontiers | Frontiers in Neurology

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SPECIALTY SECTION
This article was submitted to Neurorehabilitation,

Translation of the Fugl-Meyer assessment into Romanian: Transcultural and semantic-linguistic adaptations and clinical validation

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Upper Extremity — Movement Inventory

*15 standardized movements across 4 severity levels (aside **normal = no** motor deficit, and respecitvely **complete paralysis**)*

M1	Flexor / Extensor Synergy	Synergy	M8	Circumduction	Wrist
M2	Hand to Lumbar	Synergy mix	M9	Hand Flexion & Extension	Hand
M3	Hand to Lumbar (left)	Synergy mix	M10	Hook Grasp	Hand
M4	Shoulder Abduction	Selective	M11	Thumb Adduction	Hand
M5	Pronation / Supination	Selective	M12	Pince Grasp	Hand
M6	Wrist Dorsi/Volar Flexion (elbow 90°)	Wrist	M13	Cylinder Grasp	Hand
M6b	Wrist Dorsi/Volar Flexion — slow	Wrist	M14	Spherical Grasp	Hand
M7	Wrist Dorsi/Volar Flexion (elbow 0°)	Wrist	M15	Coordination — knee to nose	Coord.

e.g.: M2 — Hand to Lumbar

FMA Upper Extremity · Synergy Mix · Multi-camera demonstration

Synergy Mix

FMA Protocol — M5

Movement
”Hand to lumbar spine — patient touches the back of the hand to the lumbar region”

Starting position

Arm at side, elbow extended

Instruction
"Place the back of your hand on your lower back"

FMA section
Synergy mix (Section 3) — requires elements from both flexor and extensor synergy

Scoring
0 — cannot initiate
1 — hand reaches but not lumbar
2 — full performance

Clinical note

Tests the ability to combine synergy components — a key transition in Brunnstrom recovery

Cam 1 ~ Top view	Cam 2 — Lateral view	Cam 3 — Frontal view
Cam 1 — Top view 45° overhead	*Cam 2 — Lateral view 90° right*	*Cam 3 — Frontal view 0° front*

All 3 cameras hardware-synchronized · Start simultaneously · 60 fps

III. Volitional movement mixing synergies, without compensation		none	partial	full
Hand to lumbar spine hand on lap	cannot perform or hand in front of ant-sup iliac spine hand behind ant-sup iliac spine (without compensation) hand to lumbar spine (without compensation)	0	1	2

*Fugl-Meyer AR, et al. Scand J Rehabil Med. 1975;7(1):13-31
*Onose G, et al. Front Neurol. 2023;13:1022546
*Brunnstrom S. J Am Phys Ther Assoc. 1966;46(4):357-375

Customized (different – *see below*: *,**) **Classification Framework**

* https://pmc.ncbi.nlm.nih.gov/articles/PMC5299057/ ** https://pubmed.ncbi.nlm.nih.gov/41606212/

Normal 59-60p (”without reflexe items”*)	Full movement quality. Serves as the digital twin reference baseline. Clinically: no neurological deficit.

Four-levels *of* ***severity*** *classification/ stratification within the FMA paradigm*:

Mild 48-58p	Slight impairment. Movement largely preserved. Minor compensatory strategies. FMA score near maximum.
Moderate 30-47p	Moderate impairment. Visible compensation. Synergy influence present. Selective control partially retained.
Marked 13-29p	Marked impairment. Synergy patterns dominate. Selective movement requires maximal effort. FMA mid-range.
Severe 1-12p	Severe impairment. Near-complete loss of selective motor control. Flaccidity or strong spasticity. Low FMA.

Key addition: 'Normal' level — not in the original FMA — essential for digital twin reference model, as well as ‘complete’: impossible vouluntary movement (0).

*Woytowicz EJ, Rietschel JC, Goodman RN, Conroy SS, Sorkin JD, Whitall J, McCombe Waller S. Determining Levels of Upper Extremity Movement Impairment by Applying a Cluster Analysis to the Fugl-Meyer Assessment of the Upper Extremity in Chronic Stroke. Arch Phys Med Rehabil. 2017 Mar;98(3):456-462. doi: 10.1016/j.apmr.2016.06.023. Epub 2016 Aug 9. PMID: 27519928; PMCID: PMC5299057.

Digital Twin & Telerehabilitation (Virtual Coaching)

From clinical scale to remote coaching — the STRATIF-AI vision

Access

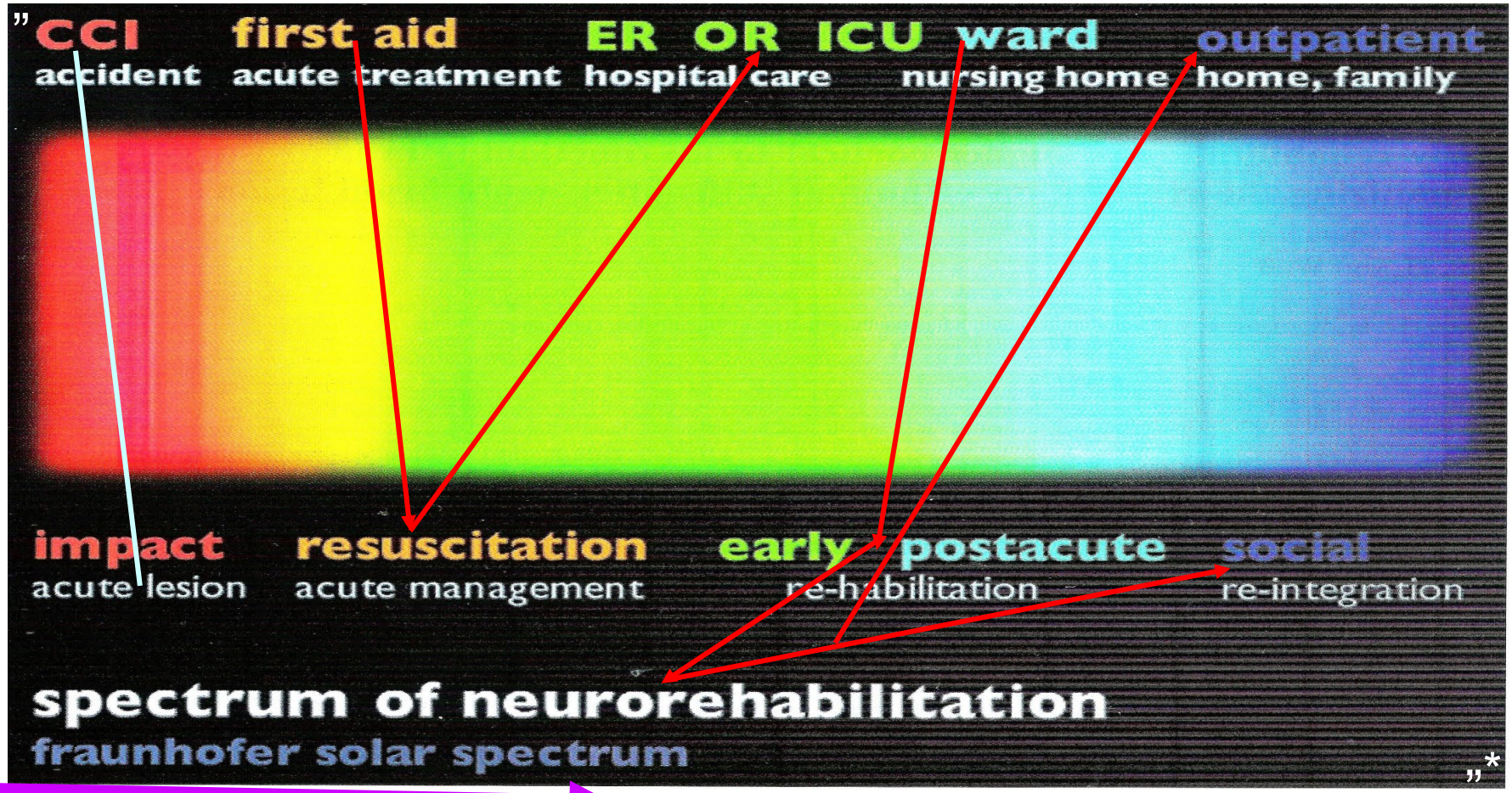
Validated motor assessment **without** travel. Patients in **remote** areas or with limited mobility included.

Continuity

Continuous monitoring between clinical visits (it frames including within the ”continuous stratification” basic concept of our project). Dynamic timely adjustment of rehabilitation protocols.

Objectivity

Standardized 3D kinematics remove inter-rater variability. Reliable longitudinal comparison.



The "**spectrum**" of the "**continuum**" approach in **NeuroRehabilitation**

(by *von Wild KR - Early rehabilitation of higher cortical brain functioning in neurosurgery, humanizing the restoration of human skills after acute brain lesions. Acta Neurochir Suppl. 99:3-10, 2006)

3D Kinematic Analysis — From Lab to Clinic (and not only ...)

The next logical step in objective motor assessment after stroke

Why 3D kinematics?

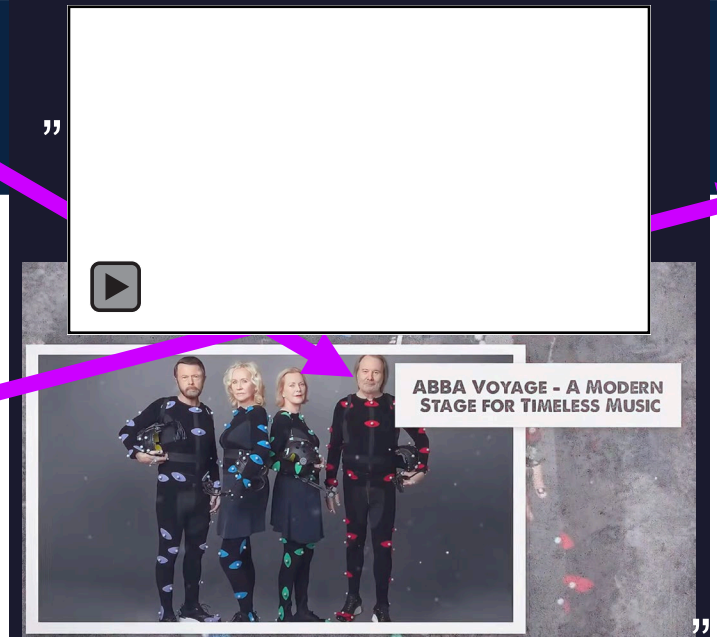
3D motion analysis quantifies what clinical observation can estimate more demanding: joint angles, velocity profiles, movement smoothness, and trajectory deviation from normal. As computational power and camera hardware have become increasingly affordable, kinematic assessment is transitioning from specialized movement/ gait analysis laboratories to routine clinical environments.

Gold standard — marker-based systems

Optical marker-based systems (e.g. **Vicon**, Qualisys) remain the reference standard — sub-millimeter accuracy, full biomechanical modeling, validated across decades of clinical research. Limitations: high cost (>€50k), chronophagic markers placement, uncomfortble for patients – especially for continuous monitoring/"stratification", specialized operators, and a controlled lab environment — making routine clinical deployment impractical.

Markerless — the accessible alternative

RGB camera-based pose estimation achieves clinically relevant accuracy at a fraction of the cost — no markers, no wearables, deployable in any room. Recent validation studies confirm correlation with marker-based systems for key upper and lower limb kinematic parameters.



	Marker-based	Markerless
Accuracy	★★★★★	★★★★☆
Cost	Very high	Low
Setup time	30-60 min	< 5 min
Clinical use	Lab only	Any setting
Wearables	Required	None

*Unger T, et al. arXiv. 2024. arXiv:2411.14992.
*Needham L, et al. J Biomech. 2022;138:111112.
*Wishaupt K, et al. Sci Rep. 2024;14:11910.
*Carse B, et al. Physiotherapy. 2013;99(4):347-351.

La nivel macro-structural, se consideră că cele 3 curburi fiziologice (lordozele: cervicală – regiunea cervicală este inclusiv o importantă zonă "furnizoare" de aferențe proprioceptive – și lombară și cifoza toracală) contribuie major la stabilitatea trunchiului și implicit, a întregului corp.

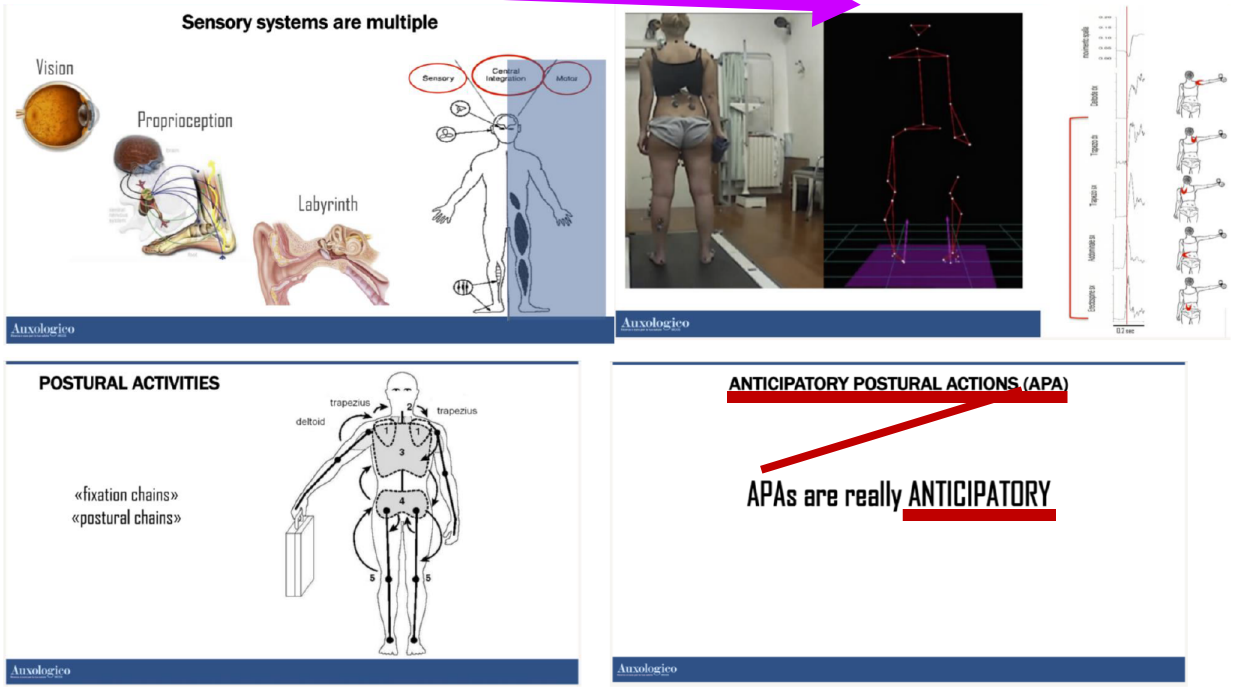


Fig. 2.6. "PRM: Sensory-motor integration. At the origins of a function-oriented rehabilitation in neurological impairments." – imagine reprodusă, cu amabila sa aprobare scrisă, după Luigi TESIO Professor, Physical and Rehabilitation Medicine, the University of Milan; Director, Department of Neurorehabilitation Sciences, Instituto Auxologico Italiano, Milan, Italy

From Clinical Observation to Markerless 3D Kinematics

Why this approach — and how does it differ? **Assessment first.** Games later. *Clinical validity from the start.*

The Problem

- FMA is the gold standard but requires a trained clinician present
- Time-consuming — difficult to apply remotely or continuously
- Inter-rater variability limits longitudinal comparison
- No affordable, markerless 3D solution with clinical grounding

Existing Approaches

- Lab-based systems (**Vicon**, Qualisys) — marker-based, gold standard accuracy, but high cost and clinic-only
- Game-based/ exergame systems * — but we consider they are applicable **only** in mild-to-moderate motor impairment, as patients with marked or severe motor deficits cannot engage efficiently with gameplay-based interfaces
- Assessment inferred from gameplay — game comes first
- Mostly 2D camera, no full 3D reconstruction
- No 'Normal' reference baseline for digital twin comparison

Solution

- **Assessment comes first** — built on the FMA protocol paradigm and our customized classification of the motor deficit
- 3 synchronized cameras → full 3D reconstruction
- Markerless, no wearables, low-cost hardware
- 'Normal' level as digital twin reference baseline

**Tannús J, Valentini C, Naves E. npj Digital Medicine. 2026. doi:10.1038/s41746-026-02383-1*

”postural control and movement accuracy. Snowball Fight can be played individually or with a partner. In individual mode, the patient plays against a computer-controlled enemy penguin that is throwing snowballs at the patient. If played with a partner, the partner plays the role of the enemy penguin.

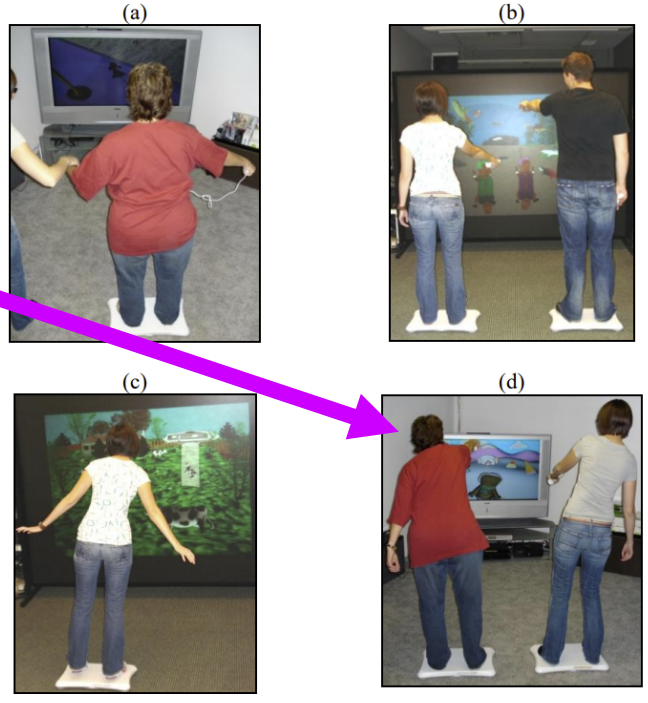


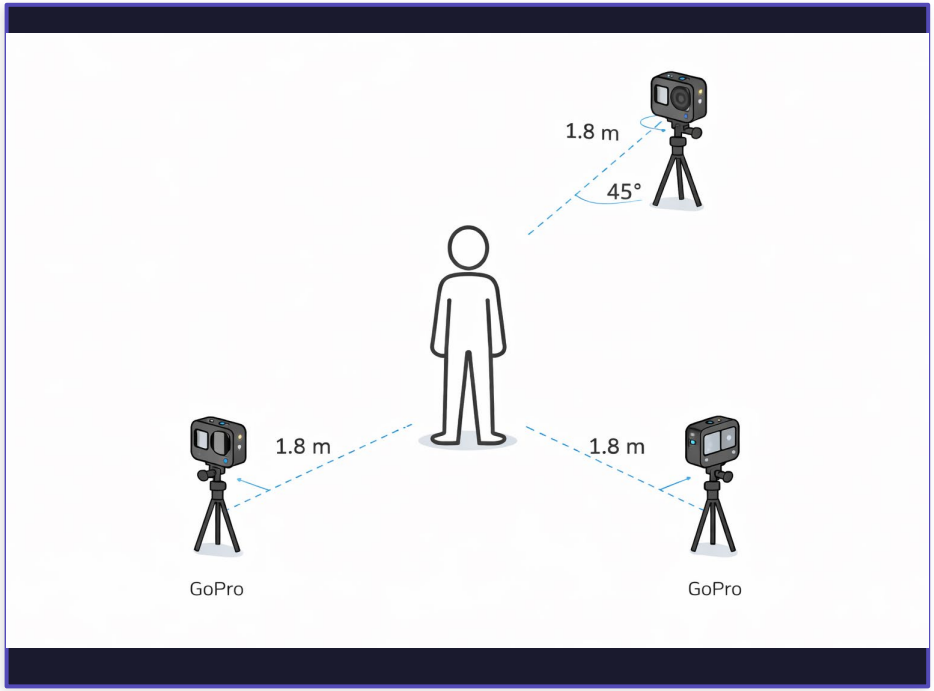
Figure 1: Patients interacting with: a) Mouse House, b) Startle Fish, c) Alien Invasion, d) Snowball Fight

In the Mouse House activity, the patient plays the role of a mouse that searches through a large virtual house to find pieces of cheese. In this activity, the patient uses a Wii Balance Board and a Wii Remote. The patient can sit on, stand on, or kneel on the Balance Board and use it as a navigation interface by shifting their weight to move the virtual mouse. This activity challenges the patient to exercise balance and movement precision. This activity can be played individually or with a partner. In partner mode, ...”*

*Anderson F, Annett M, Bischof WF. Lean on Wii: physical rehabilitation with virtual reality Wii peripherals. Stud Health Technol Inform. 2010;154:229-34. PMID: 20543303.

Part 2 — Technical Implementation

Recording · Extraction · Reconstruction



3× GoPro Hero 12 · 1080p · 60fps · hardware-synchronized

What we set out to do

Record and reconstruct 3D movement of the upper extremity for all 15 FMA movements across 5 severity levels — without markers, without wearables.

How we recorded

Three synchronized cameras placed at different angles capture the subject from top, front, and side simultaneously.

How we extracted movement

MediaPipe Holistic identifies 34 body landmarks per frame. Each landmark's position in 3D space is computed by combining information from all three camera views.

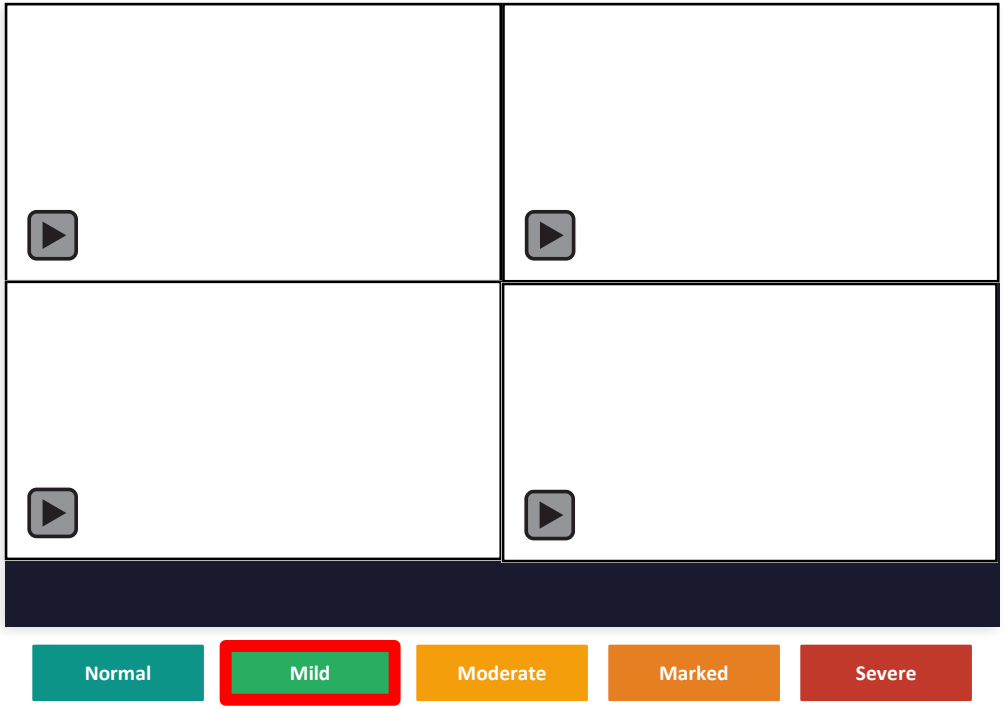
What we reconstruct

Full 3D joint trajectories — shoulder, elbow, wrist, hand — frame by frame, at 60 frames per second.

*Lugaresi C, et al. arXiv:1906.08172 (2019)
*Zhang Z. IEEE Trans PAMI. 2000;22(11):1330-1334
*Hartley R, Zisserman A. Multiple View Geometry. Cambridge UP; 2003.

From Video to 3D Data — What We Extracted and Stored

34 body landmarks · 60 fps · 811k rows of kinematic data · ready for analysis



Landmark extraction

34 body landmarks identified per frame across all three cameras — shoulders, elbows, wrists, hips, hands. Each landmark has X, Y, Z coordinates at every frame.

3D reconstruction stored*

All landmark coordinates triangulated and saved in a structured dataset — 811,000 rows covering 15 movements × 4 severity levels. Data is ready for any downstream analysis.

Kinematic analysis — what becomes possible**

Joint angles, movement speed, range of motion, and trajectory shape can all be computed from the stored data — at any point, without re-recording.

Foundation for future scoring

Because a Normal reference level was recorded, any future patient movement can be compared against it — enabling automated deviation scoring and rehabilitation monitoring.

*Savitzky A, Golay MJE. Anal Chem. 1964;36(8):1627-1639
**Virtanen P, et al. Nat Methods. 2020;17:261-272.

From Clinic to Technology

What could we measure that clinical observation alone cannot (at least as fast and easy)?

Clinical observation	Digital measurement
Clinician watches synergy pattern	3D joint angles per frame - deviation from **normal** trajectory
Elbow doesn't fully extend	Elbow angle time series — range of motion quantified in degrees, **without the need for a physical goniometer**
Movement is slow/ tremulous	Velocity profile- detects tremor, clonus, and movement fragmentation
Hand doesn't open fully	Palmar opening width — distance (cm) between finger tips (II-IV) to thenar/hypothenar eminences (MCP based processing)
Coordination is poor	Deviation of index tip from ideal knee-to-nose trajectory (cm)

Part 2

Technical Implementation

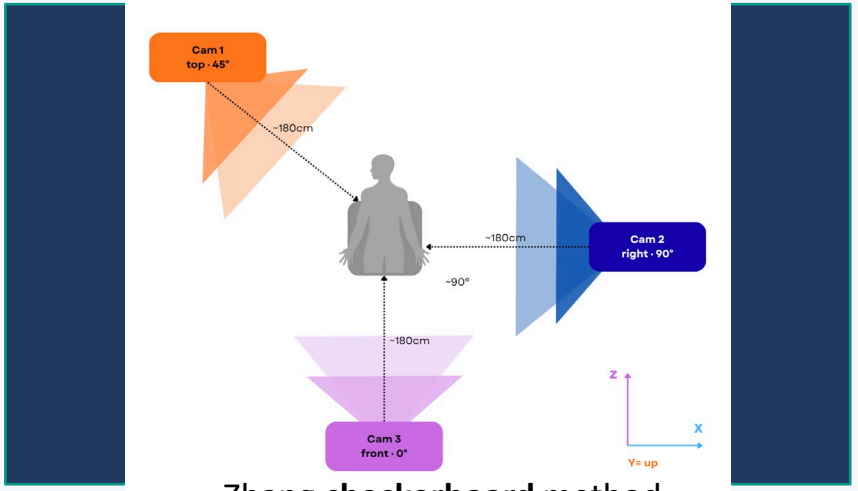
Recording · Keypoint Extraction · 3D Reconstruction · Validation

Recording Setup

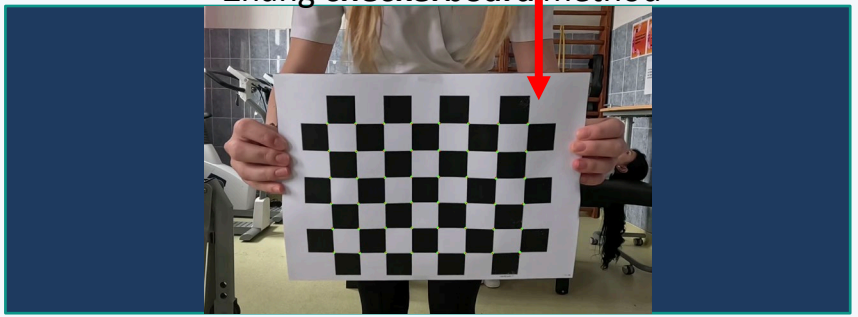
Multi-camera synchronized acquisition · Upper extremity session

Parameter	Value
Camera model	3× GoPro Hero 12 Black
Resolution	1920 × 1080 px (1080p)
Frame rate	60 fps
Synchronization	Hardware-synchronized
Camera distance	~1.8 m from subject
Cam 1	Top · 45° overhead
Cam 2	Right · lateral 90°
Cam 3	Front · 0° frontal

Subject: skilled physiotherapist · simulated all 4 severity levels per movement



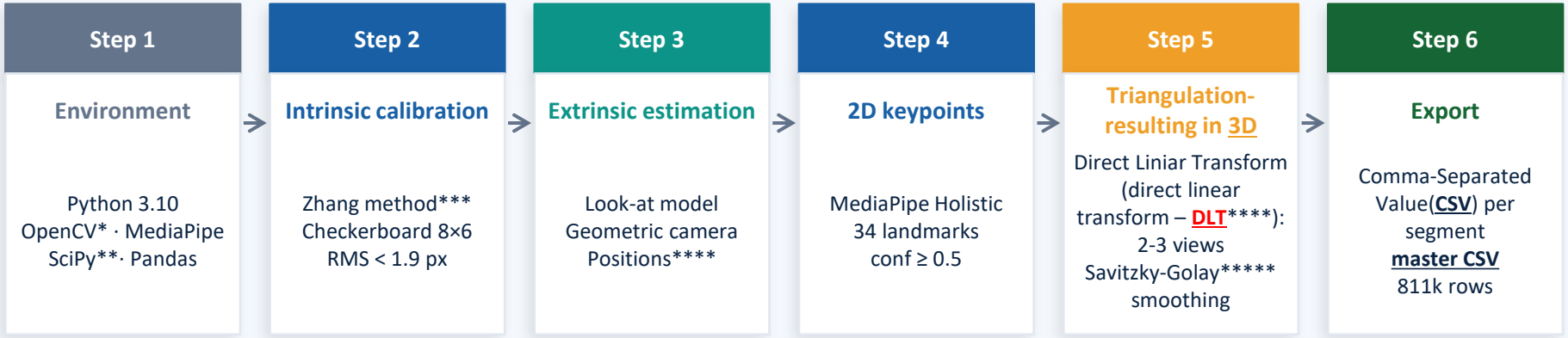
Zhang **checkerboard** method



*Zhang Z. A flexible new technique for camera calibration. *IEEE Trans Pattern Anal Mach Intell.* 2000;22(11):1330-1334.

Processing Pipeline — Overview

Six-step automated pipeline: raw video → 3D kinematic analysis



*Bradski G. The OpenCV library. Dr. Dobb's Journal. 2000;25(11):120-125.
**Virtanen P, et al. Nat Methods. 2020;17:261-272.
***Zhang Z. A flexible new technique for camera calibration. IEEE Trans Pattern Anal Mach Intell. 2000;22(11):1330-1334.
****Hartley R, Zisserman A. Multiple View Geometry in Computer Vision. 2nd ed. Cambridge University Press; 2003.
*****Savitzky A, Golay MJE. Anal Chem. 1964;36(8):1627-1639.

Keypoint Extraction & 3D Reconstruction

MediaPipe Holistic · Direct Linear Transform (DLT) triangulation

MediaPipe Holistic*

- Simultaneous Pose + Hands in one pass 33 pose + 21 pts/hand = 75 total;
- 34 targeted per our protocol
- Shoulders, elbows, wrists, hips, knees, nose — all fingers MCP + tip
- Confidence score per landmark (threshold ≥ 0.5 applied)

*Lugaresi C, et al. arXiv. 2019. arXiv:1906.08172.

DLT Triangulation

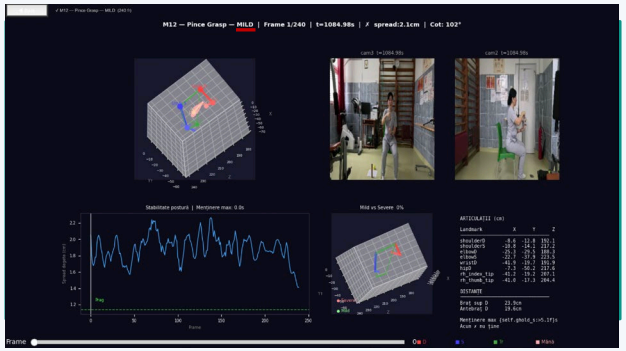
- System Ax = 0 built from 2D observations across cameras
- Solved via Singular Value Decomposition (**SVD**) 2 cameras minimum;
- **3 cameras preferred**
- Savitzky-Golay smoothing: window=11 frames, order=3**,***

**Savitzky A, Golay MJE. Anal Chem. 1964;36(8):1627-1639.

***Virtanen P, et al. Nat Methods. 2020;17:261-272.

3D Kinematic Viewer — Upper Extremity

Interactive visualization with synchronized video overlay



- Frame-by-frame slider synchronized with multi-camera video
- **Mild vs. severe overlay — same movement, same frame proportion**
- Joint angles, segment lengths, pronation/supination angle displayed live
- Grasp stability timer for M10-M14 · deviation plot for M15

Results & Anatomical Validation

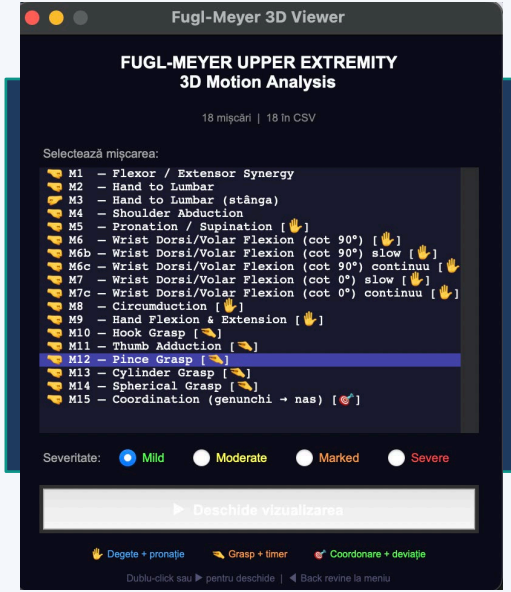
Dataset statistics and geometric plausibility — upper extremity

15
UE movements recorded

4
severity levels per movement

34
landmarks per frame

811k
rows in master CSV



Anatomical validation — Drillis & Contini (1966)* proportionality constants:

Segment	Measured (cm)	Reference (cm)	Error (%)
Upper arm (right)	27.0	29.2	8%
Forearm (right)	23.2	22.9	1%
Shoulder width	23.1	28.0	17%

Upper extremity mean error under 10% *for the selected segments.* ***Shoulder width: seated position + occlusion → not representative of pipeline error.***

*Drillis R, Contini R. *Body Segment Parameters.* Tech. Rep. 1166-03. New York University; 1966.

Limitations & Next Steps

Current constraints and planned validation pathway

Current Limitations

- Single-subject dataset (n=1)
- No ground truth validation against optical marker systems
- Extrinsic calibration estimated geometrically (~8% mean error)
- Left hand partial **occlusion** in some movements (cam2)
- M10-M14 timestamp
- refinement needed

Planned Next Steps

- Multi-subject recording
- (**patients** + healthy controls)
- Validation vs **Vicon/optical**
- marker ground truth
- Simultaneous checkerboard
- calibration (all 3 cameras)
- Biomechanical dictionary
- (dynamic time warping – DTW + reference intervals)
- **long-short term memory** (LSTM) Autoencoder for
- automated severity scoring

Conclusions — Part I

- A low-cost, markerless pipeline successfully reconstructs FMA upper extremity movements in 3D digital application – for the DT
- The customized 4-level classification + normal baseline (and/or complete paralysis) enables the Digital Twin's comparisons
- Anatomical plausibility confirmed: mean upper limb segment error under 10% using the Drillis & Contini method.
- Framework ready for **telerehabilitation**: continuous remote stratification, automated scoring development, and virtual coaching

Coming next — Part II:

Markerless 3D Analysis of Lower Extremity Movements Mimicking Hemiplegia Using the Fugl-Meyer Assessment Paradigm — Toward a Virtual Coaching System

Lower extremity specifics · LL results · Virtual coaching roadmap · LSTM autoencoder

CONSTRUIRE,
C'EST UN DON...
THANK YOU
FOR YOUR
ATTENTION !