European Motor Control Conference (EMC²)

3rd Edition — Program, Practical info and Abstracts

August 26–28th, 2026 · UCLouvain · Maisin Auditorium, Brussels

Program - Day 1 — Wednesday, 26 August 2026

Time	Presentation
08:30–09:00	*Registration & Welcome Coffee*
09:00–09:10	*Opening Remarks*
09:10–09:50	**A The Representation of Novel Dynamics** ***David W. Franklin***, *Sae Franklin, Raz Leib — Technical University of Munich*
09:50–10:10	**1 Extrapolation of learnt motor skills outside training experience in humans and artificial agents** ***Hari Kalidindi***, *Pieter Medendorp — Radboud University*
10:10–10:30	**2 Learning and interference in inverted steering across reversed bicycle and virtual steering tasks** ***Pascal Nietschmann***, *Raz Leib, David W. Franklin — Technical University of Munich*
10:30–11:00	*Coffee Break*
11:00–11:20	**3 The Mario-Kart Effect – Confusion of Agency in Continuous Motor Control** ***Kai Streiling***, *Loes C.J. van Dam — Technical University of Darmstadt*
11:20–11:40	**4 Human spinal cord sensorimotor dynamics during voluntary movement preparation** ***Cindy Marquez***[1], *Matthias Deliano*[1], *Gina Kreitlow*[2], *Lars Büntjen*[3], *Max-Philipp Stenner*[1,3] — [1]*Leibniz-Institut für Neurobiologie;* [2]*Hochschule Magdeburg-Stendal;* [3]*Universitätsklinikum Magdeburg*
11:40–12:20	**B Measurement of the impedance-length-relation in muscle fibers** ***Matthew Millard***, *Sven Weidner, Andre Tomalka, Tobias Siebert — University of Stuttgart*
12:20–13:40	*Lunch Break*
13:40–14:20	**C Motor control is based on a universal optimal feedback control policy** ***Emmanuel Guigon*** *— Sorbonne Université*
14:20–14:40	**5 Stochastic optimal control simulations reveal how sensorimotor noise shapes human walking variability** ***Lars D'Hondt***[1], *Maarten Afschrift*[2], *Friedl De Groote*[1] — [1]*KU Leuven;* [2]*Vrije Universiteit Amsterdam*
14:40–16:20	*Poster Session + Coffee break*
16:20–16:40	**6 A Big Data Approach to Motor Control through Machine Learning** ***Elizabeth Thomas***, *Florian Chambellant, Jérémie Gaveau, Charalambos Papaxanthis, Davy Laroche, Thierry Pozzo* *— Université Bourgogne Europe*
16:40–17:00	**7 Threat of pain reorganizes lower-limb muscle synergies during human walking** ***Jennifer Burgos Tirado***[1,2], *Guillaume Léonard*[2], *Thierry Lelard*[1], *Flore Le Blanc*[1], *Maryne Cozette*[1] — [1]*Université de Picardie Jules Verne;* [2]*Université de Sherbrooke*
17:00	*End*

Day 2 — Thursday, 27 August 2026

Time	Presentation
09:10–09:50	**D Limits to balance control under perturbed proprioceptive feedback** ***Eric Maris*** — *Radboud University*
9:50–10:10	**8 The time-dependent modulation of saccade amplitude by illusory length reflects a shared representation between perception and action** ***Laurie Geers***[1], *Karine Doré-Mazars*[2], *Michael Andres*[1] — [1]*UCLouvain;* [2]*Université Paris Cité*
10:10–10:30	**9 Optimal feedback control theory accounts for tactile suppression during movement** ***Fabian Tatai***[1], *Dimitris Voudouris*[2], *Dominik Straub*[3], *Katja Fiehler*[2], *Constantin A. Rothkopf*[1] — [1]*Technical University Darmstadt;* [2]*Justus-Liebig University Gießen;* [3]*University of Cambridge*
10:30–11:00	*Coffee Break*
11:00–11:20	**10 The relative contribution of explicit and implicit processes in motor adaptation: Effects of daily activity** ***Johanna Mathiot***[1], *Charlène Truong*[2], *Célia Ruffino*[3], *Charalambos Papaxanthis*[1] — [1]*Université de Bourgogne;* [2]*UCLouvain;* [3]*Université de Franche-Comté*
11:20–11:40	**11 Decisions Under Fatigue: How Mental Fatigue Alters Human Choice Behaviour** ***Anoud Alawneh***[1], *Waltraud Stadler*[1], *Joachim Hermsdörfer*[1], *Mirta Fiorio*[2] — [1]*Technical University of Munich;* [2]*University of Verona*
11:40–12:20	**12 Modulation of visuomotor reflexive responses during unimanual and bimanual interception tasks** ***Raz Leib***, *Pascal Nietschmann, David W. Franklin* — *Technical University of Munich*
12:20–13:40	*Lunch Time*
13:40–14:00	**13 Updating and separating priors in complex sensorimotor behaviour** ***Stephan Zahno***[1], *Damian Beck*[1], *David W. Franklin*[2] — [1]*University of Bern;* [2]*Technical University of Munich*
14:00–14:20	**14 Mathematical training eliminates intuitive physics biases that motor expertise cannot** ***Ludovic Le Moullec***[1], *Ponguenewende Jessica Grace Ouedraogo*[2], *Audric Boullier*[2], *Olivier White*[1] — [1]*Université Bourgogne Europe;* [2]*ENSAM*
14:20–16:00	*Poster Session + Coffee break*
16:00–16:20	**15 Efficient gravity-related motor planning is preserved in healthy aging despite increased biomechanical and cognitive complexity** ***Amélie Calvier***[1], *Robin Mathieu*[2], *Jean-Jacques Orban de Xivry*[3], *Jérémie Gaveau*[1] — [1]*Université Bourgogne Europe;* [2]*University of Florida;* [3]*KU Leuven*
16:20–17:00	**E Arm movement control in gravity** ***Dinant Kistemaker*** — *Vrije Universiteit Amsterdam*
17:00	*End*

Day 3 — Friday, 28 August 2026

Time	Presentation
09:10–09:50	**F Differential Remapping of Inverted Whole-Body and Ankle Sensorimotor Relationships During Human Standing Balance** *Matto Leeuwis[1], Ben Rupprecht[1], Chris Dakin[2], Brandon Rasman[3], Jean-Sebastien Blouin[4],* ***Patrick Forbes[1]*** *— [1] Erasmus MC; [2] Utah State University; [3] Radboud University; [4] University of British Columbia*
9:50-10:10	**16 When Movement Fails: Adaptive Strategies for Safety and Efficiency** ***Tjasa Kunavar[1]****, Jan Babič[1], Erhan Oztop[2], Mitsuo Kawato[3] — [1]Jožef Stefan Institute; [2]Ozyegin University; [3]ATR Brain Information Communication Research Laboratory*
10:10–10:30	**17 Beyond the Average Learner: Identifying Individual Safety Preservation Strategies in Whole Body Motor Control** ***Océane Dubois****, Tjasa Kunavar, Benjamin Fele, Marko Jamsek, Jan Babic — Jožef Stefan Institute*
10:30–11:00	*Coffee Break*
11:00–11:20	**18 How motor capacity affects manual everyday life motor control along the life-span** ***Joachim Hermsdörfer****, Laura Stetter, Philipp Gulde — Technical University of Munich*
11:20–11:40	**19 Cerebellar function remains resilient under increased task demands in healthy adults up to 80 years but it is task-specific and independent of cerebellar structure** ***Anouck Matthijs[1]****, Anda de Witte[1], Dante Mantini[1], Geneviève Albouy[2], Jean-Jacques Orban de Xivry[1] — [1]KU Leuven; [2]University of Utah*
11:40–12:20	**G Compensation as motor adaptation: disentangling deterioration from strategic control in healthy aging** ***Jérémie Gaveau*** *— Université Bourgogne Europe*
12:20–13:40	*Lunch time*
13:40–14:00	**20 Development of a test battery to assess sensorimotor control in Cerebral Palsy** ***Milou van Helvert****, Pieter Medendorp — Radboud University*
14:00–14:20	**21 Proximal and distal bimanual motor control and skill learning in acute stroke** ***Coralie van Ravestyn****, Benoit Bihin, Julien Lambert, Benoit Herman, Frédéric Crevecoeur, Thierry Lejeune, Yves Vandermeeren — UCLouvain*
14:20–14:50	*Coffee Break*
14:50–15:10	**22 Investigations into the shaping of the endpoint stiffness of two-degree-of-freedom planar robotic arms** ***Thomas Pomponio*** *— UCLouvain*
15:10–15:30	**23 Co-Contraction as an Adaptive Response to Task Dynamics and Uncertainty** ***Anaïs Farr[1]****, Dorian Verdel[1], Etienne Burdet[2], Bastien Berret[1]* *— [1]Université Paris-Saclay; [2]Imperial College London*
15:30–16:10	**H Localized neuromuscular fatigue reshapes muscle synergies with lasting after-effects during voluntary multi-directional postural control** *Giacomo Costa[1], Alessandro Garofolini[2], Andrea d'Avella[3],* ***Matteo Bertucco[1]*** *— [1]University of Verona; [2]Victoria University; [3]University of Rome Tor Vergata*
16:10-16:20	*Closing remarks*
17:00	*Social Event*

Practical information

Talks & Posters

Talks Duration

Principal Investigator (PI) talks are allocated **30 minutes for the presentation**, followed by **10 minutes for questions and discussion**.

All other presentations are allocated **15 minutes**, followed by **5 minutes for questions and discussion**.

Poster presenters

Poster format: A0 poster in portrait orientation.

Posters may be mounted during the first lunch break and will remain on display throughout both poster sessions. Please remove your poster by the end of the second poster session on Thursday, 27th. The poster session will take place in Pasteur 2 (please follow the campus signage).

How to get there

Public transport – Metro Tickets

A single journey costs €2.90 (paper ticket) or €2.40 (contactless bank card, smartphone) and allows unlimited transfers within 60 minutes. You can easily tap in at the yellow or red validators and out using your contactless bank card, smartphone, or smartwatch. If you switch lines or jump on a tram/bus, you must tap your card again at the validator for a free transfer (provided it is within the 60-minute window).

Conference Venue

Université catholique de Louvain (UCLouvain)
Auditoires Centraux building – **Auditoire Maisin**
Avenue Emmanuel Mounier 51, 1200 Brussels

The walk takes about 2–3 minutes (approximately 200 m) from Alma metro station.
Directions:

1. Take metro **Line 1** (direction **Stokkel**).
2. Get off at **Alma Metro Station** and take **Exit 3**
3. Take the stairs up (or the escalator/elevator) and follow the path on the right, following the signs for "**Faculté**", "**Auditoires**".
4. Take the stairs down.
5. Cross the pedestrian bridge over Avenue Emmanuel Mounier.
6. The **Auditoires Centraux building** will be directly ahead.
7. **Auditoire Maisin** is located on the 1st floor.

Social Event

Grand Hospice - **Le Jardin des Hospices**
(https://www.grand-hospice.brussels/jardin/)

Address:

Rue du Grand Hospice 7, 1000 Brussels

How to get there:

Metro Line 1 (direction Weststation) takes you near Grand Hospice in 25 minutes. The walk takes about 5 minutes (approximately 400 m) from Catherine metro station.

Directions:
Take metro **Line 1** (direction **Weststation**).
Get off at **Catherine Metro Station**.
Take the **Populierstraat**, keep left on the **Begijnhof**, and walk down the **Fermerijstraat**. You are in front of the **Grand Hospice**, walk straight to enter the garden.

We look forward to seeing you there

Abstracts

Talks

A. The Representation of Novel Dynamics

David W. Franklin[1], Sae Franklin[1], Raz Leib[1]

[1] Technical University of Munich

To precisely control our movements, the sensorimotor control system builds representations of the external world. However, the encoding of these representations – whether we encode our control as a function of specific kinematic or kinetic variables – is still unknown. For example, velocity dependent dynamics could be represented within the brain within a Cartesian, intrinsic or object reference frame. However, the experimental results are conflicting: each previous study provided evidence for one of the representations with no consistency across findings. Here, we propose a different framework in which the sensorimotor control system uses multiple representations, allowing it to flexibly tune its representations to task demands. We directly test this by showing that the representation of external forces is governed by the nature of the experienced forces. First, we present our unifying model of the representation that can explain the previous conflicting results. Second, we show how these representations can be modified as additional sensory information comes in to tune these mixture-models to the external dynamics. This flexibility and redundancy in the representations allows the precise tuning to any specific task within our complex environment, explaining our expertise in a wide range of tasks.

B. Measurement of the impedance-length-relation in muscle fibers

Matthew Millard[1], Sven Weidner[1], Andre Tomalka[1], Tobias Siebert[1]

[1] University of Stuttgart

Haptic manipulanda experiments show that the arm's endpoint stiffness and damping (impedance) are manipulated by the central nervous system when learning new tasks: impedance is high when a task is unfamiliar and decreases with experience. Endpoint impedance is ultimately produced by active muscles, since the impedance of muscle varies with active force. To simulate motor learning accurately, it is important to model muscular impedance correctly.

Although the impedance of muscle fibers has been studied in terms of its sensitivity to temperature and pharmacological manipulations, the impedance-length relationship has not yet been measured. We measured the force response of active muscle fibers to small-amplitude stochastic perturbations across a range of lengths from 0.55 to 1.45 optimal fiber lengths. To process this data, we first compensated for the bandwidth limitations of the force sensor before transforming the length and force signals into the frequency domain. We identified the transfer function that best represents how the muscle fiber responded to the stochastic length perturbations using Welch's method. The resulting transfer function shows that both the stiffness and damping response of the muscle fiber correlate with the force-length relation, though the variation increases with frequency.

C. Motor control is based on a universal optimal feedback control policy

Emmanuel GUIGON [1]

[1] Sorbonne Université

The purpose of motor control is to generate the guidance of body configurations toward spatial goals. A central difficulty to address is the mastering of body and world dynamics, e.g. internal forces due to interacting degrees of freedom, external forces due to interaction with objects, with gravity, ... In the framework of computational motor control, how external forces are dealt with is debated. On the one hand, it has been proposed that external forces (due to perturbations) are compensated independent of internal forces (Shadmher and Mussa-Ivaldi, 1994, J Neurosci 14:3208). On the other hand, external forces might be integrated into a body+perturbation dynamics and controlled accordingly (reoptimization model; Izawa et al., 2008, J Neurosci 28:2883). Both ideas fail to explain adaptation to a velocity-dependent force field (Moullet et al., 2022, PLoS Comput Biol 18:e1010470). A third proposal is that motor control is based on a universal (task-independent) optimal feedback control policy tuned to the body dynamics and external forces are taken into account through dedicated task goals (Guigon, 2023, Psychol Rev 130:23). Here, we show that this proposal can explain the production of movements in the gravitational field and balance of a stick on the tip of the finger. The core idea is that task goals are built from a proportional-integral-derivative function of the state of the body (finger) and the object (stick). The results provide further support to the idea that motor control uses a universal control policy.

D. Limits to balance control under perturbed proprioceptive feedback

Eric Maris[1]

[1] Radboud University

The three main sources of sensory feedback for balance control are the vestibular organ, the retina, and the muscle spindles (the main proprioceptive sensory organ). If one of these sources is degraded, sensory compensation occurs through upweighting the contribution of the remaining sensory modalities. However, there is no systematic account of the limits of this sensory compensation. This study leverages the unique properties of a bicycle simulator to provide such an account.

Balancing a bicycle offers a key advantage over walking for studying balance control: the muscles with a balance-relevant sensory function (torso and legs, which register feedback about the center of gravity via gravity-dependent muscle tension) differ from those with a motor function (arms, which generate balance-restoring control actions). Using a swing saddle, gravitational information in the torso muscle spindles was perturbed, while that in the leg muscle spindles was removed.

The study quantified the limits of sensory compensation under perturbed proprioceptive feedback. In one condition, participants balanced with perturbed proprioceptive feedback while blindfolded (leaving only vestibular feedback for compensation). In a second condition, they could see (allowing visual feedback to contribute to compensation). The results highlight the constraints of sensory reweighting when proprioceptive feedback is degraded, offering insights into the hierarchical reliance on vestibular and visual inputs for maintaining balance.

E. Arm movement control in gravity

Dinant Kistemaker[1]

[1] Vrije Universiteit Amsterdam

We investigated whether gravity influences fast goal-directed planar arm movements by having participants perform point-to-point outward and inward 2 DoF movements in a reclinable chair, varying orientation relative to gravity from horizontal (0°) to vertical (90°) in steps of 15°. Strict temporal (400 ± 100 ms) and spatial constraints ensured comparable movement conditions across orientations. Consistent with the literature, we found significant differences between inward and outward movements in terms of movement curvature (xdev) and time-to-peak-velocity (tpv), which were consistent across all chair reclining angles. However, when comparing inward movements at different angles and outward movements at different chair angles, we found no significant effect of gravity on both xdev and tpv. Using an optimal control musculoskeletal model of the human arm, we predicted movement trajectories for several commonly proposed cost functions. We found that only jerk-based (kinematic) cost functions reproduced the experimentally observed movement patterns, while cost functions incorporating muscle activation (e.g. control effort) or muscle output (e.g. muscle force, muscle torque) predicted clear gravity-dependent effects that were not present in the experimental data. In conclusion, we found no effect of gravity on goal-directed arm movements; the observed differences in kinematics were due only to differences in movement direction. In addition, only kinematics-based cost functions generated movements similar to those observed experimentally.

F. Differential Remapping of Inverted Whole-Body and Ankle Sensorimotor Relationships During Human Standing Balance

Leeuwis Matto[1], Ben Rupprecht[1], Chris Dakin[2], Brandon Rasman[3], Jean-Sebastien Blouin[4], **Patrick Forbes**[1]

[1] Erasmus MC, [2] Utah State University, [3] Radboud University, [4] University of British Columbia

Standing balance depends on linking motor commands to sensory consequences of both ankle and whole-body motion. Although these relationships are often treated as fixed, previous work showed that humans can adapt when the relationship between motor commands and whole-body sensory feedback is inverted, suggesting that vestibular contributions to balance can be transformed. However, this learning occurred while ankle motion remained normal relative to motor commands, leaving unclear whether similar adaptation is possible when ankle-related feedback is also inverted. It is also unknown whether such transformations produce aftereffects when normal standing is restored, a key marker that adaptation has altered the underlying sensorimotor representation. Here, we tested how humans adapt to inverted ankle and whole-body sensorimotor relationships during standing balance, how this adaptation develops over time, and whether it produces aftereffects during subsequent normal standing. Participants rapidly adapted to isolated inversion of the ankle relationship, but this produced no measurable aftereffects. Isolated inversion of the whole-body relationship was also learned rapidly, but produced modest aftereffects, indicating partial persistence of the adapted state. In contrast, simultaneous inversion of both relationships led to slower adaptation and dramatic aftereffects when normal balance was restored. To identify the source of these disruptions, we tested ankle inversion without whole-body motion feedback and found that this isolated inversion could not be learned. These findings show that sensorimotor relationships in standing balance differ in adaptive flexibility, with whole-body sensory feedback providing both a dominant reference for resolving altered balance control and a primary source of persistent adaptation.

G. Compensation as motor adaptation: disentangling deterioration from strategic control in healthy aging

Jérémie Gaveau [1]

[1] Université Bourgogne Europe

Aging changes movement, but not every age-related change is a deficit. In motor behavior, compensation is often used as a loose label for differences between younger and older adults, although such differences may reflect deterioration, strategic adaptation, or both. I will argue that, in the context of motor aging, compensation is best treated as an adaptive response to motor-system deterioration that preserves—or prioritizes—functionally relevant goals.

This perspective will be developed from recent work, including a recent study comparing arm and whole-body motor control in younger and older adults. In that study, combining phasic EMG, center-of-mass analyses, optimal-control simulations, and exhaled-gas measurements, we showed that older adults preserved energetic efficiency during arm movements but not during whole-body actions. Rather than indicating a general loss of motor planning, this pattern suggests a task-dependent shift from effort minimization toward equilibrium safety. Related findings in the field similarly indicate that age-related motor changes cannot be interpreted without identifying the control processes and task goals involved.

More broadly, I will argue that studying compensation in aging requires moving from coarse measures of motor performance toward finer measures that isolate component processes contributing to performance. Global outcomes such as speed, accuracy, or strength often mix multiple control processes into a single net result. An approach focusing on a component process could help determine whether a change reflects deterioration or adaptation to deterioration. Compensation should be treated not as a descriptive label, but as a mechanistic hypothesis to be tested.

H. Localized neuromuscular fatigue reshapes muscle synergies with lasting after-effects during voluntary multi-directional postural control

Giacomo Costa[1], Alessandro Garofolini[2], Andrea d'Avella[3], **Matteo Bertucco[1]**

[1] University of Verona , [2] Victoria University, [3] University of Rome Tor Vergata

Localized neuromuscular fatigue (NMF) may challenge postural control, yet its effects on the modular organization of muscle activity during upright standing remain unclear. This study investigated whether localized NMF influences postural performance and the number and structure of muscle synergies during voluntary multi-directional postural control, and whether fatigue-related changes persist when participants are re-exposed to the task in a non-fatigued state. Twenty-four healthy adults were assigned to either a fatigue group (n = 13) or a non-fatigue control group (n = 11). Participants performed a visually guided postural task requiring them to displace their center of pressure toward four directions, while maintaining upright stance as an inverted pendulum. On Day 1, after baseline, participants repeated the task four times following either a localized fatiguing or non-fatiguing protocol. During re-exposure, participants performed the task once with the non-fatiguing protocol. Electromyographic activity was recorded from 16 lower-limb and trunk muscles, and muscle synergies were extracted using non-negative matrix factorization. Postural control performance was preserved following fatigue and across repetitions. Changes in synergy number were small at the group level, although subject-specific variations may be present. In contrast, NMF induced large changes in synergy structure throughout Day 1, particularly toward the end of practice. These changes involved a different redistribution of synergy weights within synergies between groups and remained detectable during re-exposure. Even when stability and performance are preserved, retention and re-exposure reveal lasting neuromuscular coordination changes, suggesting that localized fatigue biases CNS re-weighting of muscle activation and produces measurable after-effects beyond fatigue.

1. Extrapolation of learnt motor skills outside training experience in humans and artificial agents

Hari Kalidindi[1], Pieter Medendorp[1]

[1] Radboud University

Humans act successfully in situations they have never encountered, such as walking on an icy surface for the first time rarely results in a catastrophic fall. One class of explanations attributes this capacity to physics-informed structure inference: the brain learns the generative structure of movement dynamics and uses it to extrapolate beyond experience. However, a simpler alternative, the developmental hypothesis, proposes that a lifetime of accumulated motor experience, scaffolded by innate parameter-level priors such as gravity expectations, provides sufficient coverage of the motor space that most nominally novel situations are handled through interpolation within this pre-existing repertoire, not extrapolation from inferred physical laws. We test these competing accounts using a virtual projectile throwing task. Participants learn to throw to multiple training distances under simulated gravity, then are tested without feedback at untrained extrapolation targets. Our first experiment (N=12) shows that release parameters at novel distances fall on the task manifold discovered during training — consistent with both accounts. The critical test, currently ongoing, uses altered physics in which effective gravity varies nonlinearly with distance, producing velocity–distance relationships that diverge from normal projectile motion at extrapolation targets. No one has developmental experience with such physics: the developmental hypothesis therefore predicts failure to extrapolate despite successful training-distance learning, whereas the structural inference account predicts manifold-consistent extrapolation once the new physics is discovered. This design dissociates lifetime motor coverage from online structural rule extraction as the source of human motor generalisation.

2. Learning and interference in inverted steering across reversed bicycle and virtual steering tasks

Pascal Nietschmann[1], Raz Leib[1], David W. Franklin[1]

[1] Technical University of Munich

While humans can generalize learning from one task to similar tasks, such as riding different bicycle types, a reversed bicycle with inverted steering control is initially unrideable and requires extensive practice to reorganize the steering-roll coupling. Here we aimed to reduce or eliminate balance requirements to study learning of the inverted steering mapping and interference with regular steering. In experiment 1, participants learned to ride a reversed steering bicycle with supporting training wheels. In experiment 2, participants controlled the lateral movement of a cart in a virtual reality setup using either regular or inverted steering to track a path. In the virtual task, one group of participants received no information about the steering mapping before each trial while another group of participants received explicit cues, paralleling the reversed bicycle condition where the steering configuration is known. Across experiments we implemented occasional regular steering trials (catch trials) within inverted steering practice to assess retrograde interference.

Across both experiments performance was impaired when participants first switched to inverted steering, indicating limited transfer from regular to inverted steering mapping. Catch trials showed substantial interference with regular steering early in training. However, interference decreased over time in the reversed bicycle and the virtual cue condition while it remained high in the no-cue virtual steering condition. While prior experience with normal steering does not transfer to inverted steering, explicit contextual cues reduce interference between regular and inverted steering. In contrast, the absence of contextual information results in competition between control policies.

3. The Mario-Kart Effect – Confusion of Agency in Continuous Motor Control

Kai Streiling[1], Loes C.J. van Dam[1]

[1] Technical University of Darmstadt

Experiencing agency over the consequences of our motor actions is fundamental for successful motor control and learning. Having a sense of agency (SoA) helps to disentangle self-generated sensory feedback from external sensory input generated, for example, by other agents. SoA is argued to arise from an integration of action-prediction based, sensorimotor and static, cognitive cues about the scene. Many measures of agency, however, suffer from one of two shortcomings: either they use discrete action-outcomes, e.g., button presses, which complicates generalization to more natural, continuous movements, or they query agency in retrospective judgements, which detaches the moment when agency is experienced from the time it is subjectively rated.

We propose a new method to quantify a participant's SoA by detecting from their behaviour their confusion of control between multiple acting objects in a Mario-Kart inspired continuous control task. Experimental evidence (N=20 participants) supports the multi-cue account of agency: more confusions were observed when (i) reducing static information (making the agents visually more similar) and (ii) reducing action-prediction based information (making the agents' dynamic behaviour more similar). Furthermore, we suggest a computational motor control model that infers actions based on a continuous belief of the current object under control. First simulations show that such beliefs, inferred based on a participant's actions, qualitatively reflect our behavioural findings. Paradigm and model together offer new possibilities to study how a sense of agency is formed during continuous motor control and feeds back into it.

4. Human spinal cord sensorimotor dynamics during voluntary movement preparation

Cindy Marquez[1], Matthias Deliano[1], Gina Kreitlow[2], Lars Büntjen[3], Max-Philipp Stenner[1,3]

[1] Leibniz-Institut für Neurobiologie, [2] Hochschule Magdeburg-Stendal, [3] Universitätsklinikum Magdeburg

The spinal cord serves not only as the entry point for somatosensory information but also as the final pathway for descending motor commands. Voluntary movement depends on dynamic interactions between sensory input and motor output. While evidence from non-human primates suggests that descending motor commands can modulate sensory input to the spinal cord prior to movement onset through mechanisms such as presynaptic inhibition (Seki & Fetz, J. Neurosci. 2012), direct physiological evidence for motor-related sensory modulation in the human spinal cord remains limited.

Recent advances combining non-invasive neck EEG with invasive epidural recordings now enable investigation of human spinal cord activity with high temporal resolution (Stenner, Marquez, et al., Sci. Adv. 2025), providing new opportunities to study sensorimotor interactions at the spinal level. Using this approach, we investigated whether movement preparation modulates spinal sensory processing prior to movement onset.

Participants received median nerve stimulation while preparing either a wrist flexion movement of the stimulated limb, the contralateral limb, or no movement. Preliminary findings of on-going analyses indicate effector-specific gating of early cortical sensory responses (N20/P22 components) during movement preparation. In addition, neck recordings reveal an effector-independent increase in high-frequency oscillatory activity within 16 ms after stimulation. Together, these findings suggest that movement preparation differentially modulates spinal and cortical sensory processing and may reflect a previously unrecognized enhancement of bodily signals at spinal levels, even from body parts not directly involved in movement.

5. Stochastic optimal control simulations reveal how sensorimotor noise shapes human walking variability

Lars D'Hondt[1], Maarten Afschrift[2], Friedl De Groote[1]

[1] KU Leuven, [2] Vrije Universiteit Amsterdam

Human walking is intrinsically variable. This variability is due to uncertainty in the sensorimotor system and the environment, and is shaped by both musculoskeletal dynamics (e.g. joint stiffness and damping originating from muscles) and the control strategy used to mitigate the effects of uncertainty. Yet, insight into how sensorimotor noise shapes walking variability is limited due to a lack of experimental methods to assess sensorimotor noise and control strategies during walking. Simulations that account for uncertainty can elucidate how sensorimotor noise affects movement variability, but accounting for sensorimotor noise is not common in simulations of walking. Existing simulations have hugely simplified musculoskeletal dynamics (e.g. no muscles), the control policy (e.g. pre-defined feedback loops), or sensorimotor noise sources (e.g. only motor noise). We performed stochastic optimal control simulations of walking based on a model with 9 degrees of freedom and 18 muscles to study how the magnitude of sensory and motor noise influences walking. We solved for feedforward muscle excitations and full-state time-varying feedback gains that minimised expected effort while generating periodic, and hence stable, gait patterns. Sensorimotor noise magnitude had a small effect on the mean kinematics but shaped kinematic and muscle activity variability as well as expected effort. Although simulations underestimated the magnitude of experimental positional variability, they captured its structure. In agreement with experimental results, the control policy prioritised limiting variability of centre of mass kinematics and minimal swing foot clearance over limiting joint angle variability. Hence, our simulations suggest that effort minimisation underlies these observations.

6. A Big Data Approach to Motor Control through Machine Learning

Elizabeth Thomas[1], Florian Chambellant[1], Jérémie Gaveau[1], Charalambos Papaxanthis[1], Davy Laroche[1], Thierry Pozzo[1]

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Much of the discussion around artificial intelligence has focused on generative AI with language centred problems. Instead, we propose that Machine Learning (ML), a branch of AI used for detecting patterns in existing data has much to offer in tackling some of the most bothersome problems in motor control studies. A cardinal feature of the field is the great effort spent on synchronously collecting information from several joints and muscles. Notwithstanding this effort, much of the analyses in the domain consists of proposing hypotheses concerning a few variables, followed by univariate analyses. We will suggest that ML allows for a big data approach in which multiple variables are simultaneously analysed to find the features which are the most pertinent for detecting populations or task constraints. As a technique which permits the nonlinear grouping of multiple features, it allows for the analysis of movement as it is naturally constructed - through the simultaneous displacement of several joints and the contraction of several muscles. The concatenation of multiple features allows for discrimination in cases with only weak modifications e.g. in the early phases of a movement disorder. It also allows for a reduction in the dimensionality of variable space and hence the detection of patterns which would be difficult to detect otherwise. We will illustrate all these points using examples from gait, pointing, reach-and-grasp and finally whole body pointing. We will also contrast this technique with others like non-negative matrix factorization which also analyses multiple features.

7. Threat of pain reorganizes lower-limb muscle synergies during human walking

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The nocebo effect, where negative expectations induce adverse outcomes, is known to modulate pain perception and impair motor performance. However, the underlying changes in motor coordination, specifically how the central nervous system (CNS) organizes muscle activity in anticipation of harm, remain poorly understood. We investigated the effects of expected pain on lower-limb muscle synergies during walking, a framework that quantifies the modular organization of motor control. Two experiments on independent groups of healthy individuals (Experiment 1: N=34; Experiment 2: N=14) were performed. In Experiment 1, an inert cream was applied to the posterior knee, with an instructed nocebo group told to expect pain and a control group told it was neutral. In Experiment 2, a conditioned nocebo group with prior experience of capsaicin-induced pain received the same inert cream and nocebo instruction. Muscle synergies were extracted from electromyography (EMG) of eight lower-limb muscles before and after the nocebo induction.

Results showed that neither paradigm altered the number or spatial composition of synergies. However, the instructed nocebo group exhibited a significant temporal expansion of the weight acceptance synergy governing knee stability ($p=0.027$) and failed to reduce stride length variability across trials, unlike the control group ($p=0.033$). The conditioned nocebo group showed no such effects; instead, higher kinesiophobia was associated with greater rigidity of the late swing synergy ($r = 0.815$, $p = 0.032$). These findings indicate that expectation alone can alter temporal recruitment, block motor optimization, and interact with individual fear of movement.

8. The time-dependent modulation of saccade amplitude by illusory length reflects a shared representation between perception and action

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The finding that visual recognition impairments can occur independently of deficits in visually-guided action has led to the view that visual processes split into two distinct pathways responding to the specific requirements of perception and action. While perception would compute objects' metrics relative to visual context, action would estimate the absolute metrics right before movement execution to ensure precision and avoid constant recalculation in a dynamic world. Actions should thus be insensitive to illusions induced by the visual context, regardless of object preview time. Experimental validation of this prediction has been debated due to divergent results in research on hand-object interactions. One issue concerns the motor system's ability to correct the effect of such illusions as the hand reaches the object, contrary to immediate perception.

To address this, we investigated saccadic eye movements, which can hardly be corrected once initiated. In particular, we conducted four experiments measuring the amplitude of saccades performed along horizontal lines embedded in Müller-Lyer figures carefully designed to control for center-of-gravity biases. Results showed that both saccade amplitude and length judgment were systematically modulated by the illusion beyond what could be attributed to changes in the center of gravity, its saliency, or computation time. Additionally, the illusion's influence on saccade amplitude diminished after a longer previewing time (2,000 ms) compared to a shorter one (50 ms).

These findings support the alternative hypothesis that perception and action rely on a shared visual representation that is influenced by contextual information but becomes more precise with increased processing time.

9. Optimal feedback control theory accounts for tactile suppression during movement

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Goal-directed movements generate tactile signals that are paradoxically suppressed despite their potential relevance for ongoing motor control. The computational principles that determine when and how strongly signals are suppressed remain unclear. Prevailing accounts propose that the nervous system reduces tactile sensitivity by prioritizing internal predictions over somatosensory feedback, in contrast to accounts attributing suppression to fixed peripheral gating. However, neither framework quantitatively explains suppression's temporal dynamics or its dependence on task demands. Here, we show that tactile suppression is a consequence of optimal state estimation during movement. Using optimal feedback control theory, we derived predictions for how the nervous system should dynamically weight internal predictions against somatosensory feedback as a function of uncertainty. Human participants performed reaching movements while vibrotactile detection sensitivity was measured at multiple time points. We found that suppression was strongest around movement onset and gradually weakened as the movement progressed. This weakening occurred precisely when internal uncertainty about the distance between hand and target increased, consistent with dynamic upweighting of sensory feedback. In a second condition, experimentally increasing initial positional uncertainty significantly weakened suppression during the initial movement phase, confirming that higher initial uncertainty shifts the nervous system toward greater reliance on incoming sensory signals from the outset. These results reframe tactile suppression as a behavioral signature of continuous and dynamic uncertainty-dependent sensorimotor integration rather than non-specific gating, revealing a normative principle governing tactile sensitivity during action.

10. The relative contribution of explicit and implicit processes in motor adaptation : Effects of daily activity.

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Motor adaptation depends on two distinct and complementary processes: an explicit process, involving conscious intentional correction, and an implicit process, characterized by automatic and unconscious sensorimotor recalibration. Together, these processes progressively reduce movement errors, thus improving motor performance. However, their relative contributions may vary with the availability of cognitive resources and the system's current functional state. For instance, internal factors such as cognitive load, mental fatigue, and age have been shown to influence this balance (Cisneros et al., 2024; Apreutesei & Cressman, 2024). As the time of day modulates this functional state, previous experiments conducted in our lab showed faster motor adaptation in the afternoon than in the morning, an effect driven by more efficient use of explicit strategies. This afternoon advantage may reflect underlying changes in brain state across the day. In line with this hypothesis, Shannon et al. (2013) further suggested that daily changes in brain activation and functional connectivity may result from accumulated prior neural activity. To determine whether this afternoon advantage reflects the accumulation of daily physical and cognitive activity, we designed an experiment to increase the functional state typically observed in the afternoon among morning-tested participants. Participants (n=17) completed one hour of combined cognitive and physical activity before testing. Results revealed a significant enhancement of explicit processes, reaching levels comparable to those observed in the afternoon group ($p < 0.05$). Although adaptation speed increased following the intervention, the effect was non-significant and did not fully replicate the afternoon advantage.

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11. Decisions Under Fatigue: How Mental Fatigue Alters Human Choice Behaviour

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A significant area in cognitive psychology and cognitive neuroscience is decision-making. Decision-making plays a crucial role in determining the efficiency and accuracy of movements. We often face critical decisions when mentally fatigued (MF) during or after prolonged cognitive efforts. The negative impact of MF on motor performance is mainly due to deterioration in cognitive processes, such as decision-making. Yet, the effect of MF on goal-directed movements, such as fine motor tasks and decision-making, is limited and warrants further study. This research aimed to explore whether MF influences motor actions using a modified Fitts' paradigm. We aimed to determine whether, under MF, individuals focus on reducing the mechanical costs of movement or precision.

Data were gathered from 30 healthy participants in three groups: High cognitive load (HCL), Low cognitive load (LCL), and control (no MF). They performed a two-alternative choice task; their choice tendencies and motor metrics were analyzed before and after MF induction.

Increasing task difficulty led all groups to reduce the movement costs by choosing targets at closer distances. However, after MF, both cognitive load groups selected way fewer closer targets than the control

12. Modulation of visuomotor reflexive responses during unimanual and bimanual interception tasks

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During movements, unexpected changes to the arm or the environment state can trigger feedback responses. Such responses, aimed at correcting the state and completing the task, include rapid involuntary responses, followed by later voluntary responses. For example, previous studies showed fast reflexive responses during reaching movements when the visual position of the target, the arm or the environment's background was shifted. However, all these studies tested the visuomotor feedback responses when the hand was already moving toward a target. Here, we examined the nature of these reflexive responses in an interception task where the hand was stationary during the presentation of the visual stimulus. In this task, implemented in a virtual reality setup, participants were presented with seven sticks, placed at different horizontal and vertical distances from the participants' hand. At a random time, one of the sticks began to fall, and the participant had to intercept it by moving their hand horizontally (unimanual task) or by rotating their hands, creating a horizontal movement of a cart that intercepted the falling stick (bimanual task). We show an elevated visuomotor reflexive response when the stick's initial position was vertically closer and horizontally away from the hand. In the bimanual task, we also found that the reflexive response changes between hands depending on the direction of the needed rotation. These results suggest that when reflexes are used to initiate movements, the sensorimotor system invests more resources and creates better conditions to increase success as the task becomes more urgent and difficult.

13. Updating and separating priors in complex sensorimotor behaviour

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Humans combine sensory information with prior expectations to guide action under uncertainty. Recent work suggests that this Bayesian integration extends to complex full-body tasks such as returning tennis serves. However, an important demand of naturalistic sensorimotor behaviour remains unexplored: updating priors when environmental statistics change versus separating them when different contexts apply. Motor adaptation studies have demonstrated that contextual cues play a key role in separating motor memories.

Here we examine whether humans can update and separate priors based on contextual cues in a complex sensorimotor task. Participants returned tennis serves in an immersive XR setup. In 50% of trials, the opponent's first serve landed in the net, requiring participants to respond to the second serve, thereby providing a contextual cue (first vs. second serve). To probe updating, one group experienced serve location probabilities biased toward one side, which switched to the opposite side halfway through the experiment. To test separation, another group experienced context-dependent serve probabilities: first and second serves were biased toward opposite sides while remaining balanced overall. Results show that, in the updating group, movements are biased by acquired prior expectations, which rapidly update when serve statistics change. In the separation group, data indicate that participants maintain distinct context-specific priors for first and second serves throughout the experiment, while effects are less pronounced than in the updating group. Overall, our data are consistent with previous motor adaptation research and suggest that humans can update and separate priors based on contextual cues during naturalistic behaviour in changing environments.

14. Mathematical training eliminates intuitive physics biases that motor expertise cannot

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Does motor expertise or formal mathematics shape the brain's internal models of physics? We tested 303 sports students, 19 mathematics students, and nine LLMs (two instructional profiles) in mental simulation of pendulum oscillations and free-fall trajectories. Sports students overestimated the heavy pendulum period (mass bias, $p<0.001$) and underestimated lunar gravity ($p<0.001$), treating mass as slowing the pendulum – a classic intuitive physics error. Mathematics students showed no significant deviation from Newtonian mechanics for any pendulum condition and correctly disregarded mass. For free-fall, all groups massively overestimated descent times (~8-fold, all $p<0.001$) irrespective of trajectory. LLMs with a "Maths" profile closely matched theoretical pendulum periods (mean absolute error 0.06 s) and correctly ordered the brachistochrone as fastest, whereas the "Sports" profile reproduced intuitive biases. Stratification within the sports group (sex, sport type, body mass, mathematical interest) revealed no significant modulator after correction. Formal mathematics training – not motor practice – eliminates the mass-bias in pendulum timing. However, free-fall mental simulation remains severely miscalibrated in all groups, suggesting a distinct, resilient cognitive bottleneck.

15. Efficient gravity-related motor planning is preserved in healthy aging despite increased biomechanical and cognitive complexity

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Numerous studies have shown that the brain exploits gravity as a source of “free” energy to minimize the energetic cost of action (Berret et al. 2008; Crevecoeur et al. 2009; Gaveau et al. 2021). This strategy is preserved in healthy aging during simple single-joint arm movements (Poirier et al. 2020, 2023) but is reduced during more complex whole-body movements (Mathieu et al. 2025). The present study investigated how movement complexity affects effort optimization in young and older adults during arm movements.

Twenty young adults (23.3 ± 3.2 y.o.) and twenty older adults (73.4 ± 6.7 y.o.) performed vertical arm-pointing movements around the shoulder involving different levels of biomechanical complexity: single-joint and multi-joint movements (1, 3 or 5 degrees of freedom). Muscle activity was recorded using surface electromyography, and effort optimization was quantified through a negativity index derived from the phasic EMG profile of antigravity muscles, reflecting the ability to exploit gravitational forces during movement (Gaveau et al. 2021; Poirier et al. 2022). Kinematic variables and cognitive performance were also assessed.

Young and older adults optimize their effort in the same way as complexity increases, i.e., no difference was found in the negativity index (Age x Biomechanical complexity: $F(2, 231) = 0.55$; $p = 0.576$; $\eta^2p = 0.005$), and same for age (Age effect: $F(1, 231) = 2.36$; $p = 0.126$; $\eta^2p = 0.010$).

These findings suggest that older adults exhibit preserved effort optimization, even during complex multi-joint arm movements.

16. When Movement Fails: Adaptive Strategies for Safety and Efficiency

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We propose a new framework for human motor learning in which ecological fitness shapes how the nervous system balances efficiency and safety. Because movement supports survival, motor control must not only achieve goals efficiently, but also manage the consequences of failure, including instability and injury risk. To test this idea, we developed an experimental paradigm that challenged participants with realistic whole-body squat-to-stand movements under unexpected backward force perturbations. Failures, defined as movements that caused loss of balance and required corrective stepping, became a central part of learning rather than an experimental error. Participants rapidly adapted to the perturbations and strongly reduced failures, while developing diverse strategies to avoid falling. These results suggest that motor learning is hierarchically organized. At the top level, an ecological controller selects whether behavior should prioritize safety after failure or efficiency after success. This controller updates motor plans through fast reinforcement learning when an action fails. Lower-level processes then implement the selected plan through feedback control, internal model adaptation, and feedback gain tuning. In contrast to fast plan changes, internal model learning is slower and occurs during movement execution regardless of success. This model reframes motor control as an adaptive, risk-sensitive system designed for real-world challenges.

17. Beyond the Average Learner: Identifying Individual Safety Preservation Strategies in Whole Body Motor Control

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Traditional approaches in motor control research often rely on group-level analyses that average data across participants, implicitly assuming a homogeneous population. However, this approach risks obscuring meaningful inter-individual variability, which is well documented to be influenced by factors such as age, laterality, and prior training experience. Treating such variability as noise may lead to the overlooking of behaviors in the mechanisms of motor learning and adaptation.

This work uses a data-driven framework inspired by [Tsay, 2024] to move beyond one-size-fits-all models and identify distinct behavioral profiles within participant populations. The approach combines Inverse Optimal Control with Weighted Dynamic Time Warping (WDTW)-based trajectory similarity and unsupervised clustering to group participants according to their behavioral dynamics, rather than relying on summary statistics. By operating at the level of individual trials the method captures the temporal structure of motor behavior without imposing prior assumptions about the number or nature of behavioral strategies present. Applied to postural control data, the framework investigates the trade-off between energy efficiency and safety priority through inverse optimal control, uncovering behavioral patterns that deviate substantially from group-average descriptions. Three distinct profiles emerged: a majority group that consistently prioritized safety throughout the entire perturbation sequence, and two smaller, equally sized groups showed opposite behaviors at environmental changes (perturbation onset and removal) followed by a return to baseline behavior.

Future directions include extending the approach to multivariate behavioral representations, enabling a richer and more comprehensive characterization of individual motor strategies. This framework offers a principled path toward personalized motor analysis with broad applications in rehabilitation and human-robot interaction.

18. How motor capacity affects manual everyday life motor control along the life-span

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In an ageing society, the ability to perform activities of daily living independently and successfully becomes increasingly important. While it is well known that motor capacity decreases with increasing age, it is unclear how this translates into motor control during everyday activities.
We tested 95 healthy participants aged 18-95 years. We assessed motor capacity using tasks performed at maximum speed or maximum force (Box-and-Block Test, 9-Hole Pegboard, tapping speed, power grip strength). Everyday-life performance was investigated in a living lab equipped to mimic a typical kitchen environment during 4 selected tasks (tea making, coffee making, preparing toast, and emptying a dishwasher). Using motion-capture technology (Qualisys), the kinematics of the movements of both wrists during task completion were analysed. Motor control was quantified in terms of volume, agility, speed and smoothness of hand movements.
We found a typical decline in motor capacity, starting between 40 and 60 years, depending on the task. The kinematics of hand movements during ADLs showed relatively high variability across the lifespan. Interestingly, there is an initial improvement followed by a less clear decline, except for smoothness. The correlations between capacity measures and ADL kinematics revealed two distinct areas. Higher-capacity achievements showed no correlation, indicating that capacity did not influence motor control. In participants with lower capacity, however, capacity showed a clear positive correlation with ADL kinematics. As expected, elderly participants dominated this latter group.
Our most important finding was a capacity threshold. If capacity is above the threshold, it is irrelevant for everyday motor control tasks. If, however, capacity is below the threshold, it becomes an important factor in the ability to perform ADL tasks well. And this critical relationship is particularly prevalent in elderly

subjects. One may conclude that motor capacity is a critical factor in ageing, including in manual ADL tasks, while our findings also open the door to promising interventions.

19. Cerebellar function remains resilient under increased task demands in healthy adults up to 80 years but it is task-specific and independent of cerebellar structure

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Aging is associated with widespread neural and motor changes, yet cerebellar-dependent predictive motor processes may remain relatively preserved. To examine this, we conducted a cross-sectional study investigating resilience to increasing task demands across cerebellar-specific and general motor and cognitive functions. The sample included 50 young, 80 older, and 30 older-old adults. Participants completed motor tasks (pure elbow motion, motor timing, postural stability) and cognitive tasks (mental rotation, spatial working memory), with task difficulty systematically manipulated to assess resilience. Structural and resting-state functional MRI were acquired to quantify cerebellar grey matter volume and intrinsic connectivity within cerebellar and cortico-cerebellar networks.

Cerebellar-specific motor measures, including anticipatory muscle activation and timing precision, were preserved across age groups and remained stable under increased task demands, indicating strong resilience even in advanced age. In contrast, general sensorimotor performance (postural stability) declined with age and showed reduced resilience. Within the cognitive domain, both cerebellar-related and general cognitive measures exhibited comparable age-related decline and reduced resilience. Resilience measures did not correlate across tasks, indicating task-specific effects.

Importantly, neither cerebellar grey matter volume nor resting-state functional connectivity within cerebellar, cortical, or cortico-cerebellar networks predicted performance or resilience. These findings support the existence of a cerebellar motor reserve reflected in preserved predictive motor control, while highlighting a dissociation between brain structure, intrinsic connectivity, and behavioral resilience in healthy aging. However, further research is needed to understand the mechanisms underpinning this reserve.

20. Development of a test battery to assess sensorimotor control in Cerebral Palsy

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Cerebral palsy is one of the most common neurodevelopmental disorders, affecting movement and posture but also perception and cognition. Children with Cerebral Palsy often require rehabilitation therapy to improve or maintain physical function. The RE:HOME project is a collaboration between technical and clinical partners in Europe and was initiated to improve and personalize home-based rehabilitation in these children. In this study we aim to investigate the computational mechanisms underlying sensorimotor deficits in children and young adults with Cerebral Palsy. We developed a model-guided test battery to assess multiple aspects of the control of reaching movements. The test battery consists of three relatively short experiments that focus on 1) the integration of visual and proprioceptive information, 2) the tuning of feedback responses as proposed by the minimum intervention principle, and 3) the processes underlying reach adaptation. The outcomes of these experiments can be computationally described, allowing us to infer latent variables that can inform clinicians and help them to tailor home-based rehabilitation programs to the individual needs of children and young adults with Cerebral Palsy. Here, we will present preliminary results from data collected in a lab environment in healthy adults. The goal is to use the test battery for home-based assessment of sensorimotor control in individuals with Cerebral Palsy.

21. Proximal and distal bimanual motor control and skill learning in acute stroke: Insights from comparison with healthy individuals - impairments, progressions and contributors.

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Bimanual coordination is essential for daily activities and allows to investigate how the nervous system integrates proximal and distal movements across both upper limbs. How these processes are altered in the acute phase of stroke remains poorly understood. We aimed to characterize proximal and distal bimanual motor control and skill learning (bim-MSkL) in acute stroke patients compared with healthy individuals (HI). We hypothesized that: (i) bimanual control and bim-MSkL would be partially impaired after stroke; (ii) distal coordination would be more affected than proximal control at baseline; and (iii) clinical and motor factors would predict bim-MSkL progression. Ninety-seven (sub)acute stroke patients and 60 age-matched HI completed a 3-day protocol involving proximal (shoulder–arm) and distal (hand) bim-MSkL tasks, with 10 trainings per task per day. Baseline motor, functional, and neuropsychological assessments were collected. Motor performance, coordination, learning trajectories, and progression predictors were analyzed. Stroke patients improved bimanual accuracy and coordination on both proximal and distal tasks over three days, although gains were smaller than in HI. Speed improvements remained limited. While distal control was more impaired than proximal control at baseline, this difference did not translate into distinct learning patterns, unlike in HI. Learning trajectories showed substantial heterogeneity, coherently with the observation that motor function, bimanual control, and cognitive deficits were the strongest predictors of bim-MSkL. Proximal and distal bimanual control and learning remain achievable in most mild-to-moderate acute stroke patients, despite reduced performance. Reorganization of control strategies supports individualized rehabilitation approaches integrating motor and cognitive demands early after stroke.

22. Investigations into the shaping of the endpoint stiffness of two-degree-of-freedom planar robotic arms

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We present a theoretical investigation into the stiffness control of two-degree-of-freedom planar robotic arms actuated by antagonistic artificial muscles. The objective is to regulate the dimensions and orientation of the endpoint stiffness ellipse using the bio-inspired principle of co-contraction. One potential application is in rehabilitation exercises, where patients grasp a handle at the robot endpoint and attempt to follow a predefined trajectory while the robot generates an assistive spring-like force towards the trajectory.

We considered a planar elbow manipulator and a five-bar mechanism with a focus on achieving isotropic endpoint stiffness. Building on Hogan's work on movement control, we established the relationships between endpoint, joint, and muscle stiffnesses. Our analysis indicates that isotropic endpoint stiffness can only be achieved with bi-articular muscles and within specific regions of the robots' workspace. The planar elbow manipulator achieves isotropic endpoint stiffness on a circular surface at the centre of the workspace, which represents about 40% of the workspace. The five-bar mechanism isotropic stiffness region takes the form of a ring near the periphery of the workspace and covers only 10% of the workspace. Then, we investigated methods to approximate isotropic endpoint stiffness on the rest of the workspace. The resulting stiffness ellipses show a 2:1 to 3:1 ratio between the principal directions. This poor fit illustrates the difficulty in achieving isotropic endpoint stiffness with two-degree-of-freedom planar arms and co-contraction.

Future work will investigate the creation of virtual tunnels around a trajectory with slender stiffness ellipses with principal axis perpendicular to the trajectory.

23. Co-Contraction as an Adaptive Response to Task Dynamics and Uncertainty

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The central nervous system (CNS) can rely on different sensorimotor control strategies to regulate movements in uncertain and dynamic environments. Using sensory information, it can implement feedback control to perform task-relevant corrections but is limited by sensorimotor delays and noise (Franklin & Wolpert, 2011). Alternatively, the CNS can use statistical regularities from past observations to anticipate disturbances through feedforward control, reflected in preparatory changes of limb mechanical impedance via muscle co-contraction (Leib et al., 2024). Recent computational approaches suggest that skilled sensorimotor control stems from a context-optimal combination of such feedback and feedforward control (Yeo et al., 2016; Berret & Jean, 2020; Berret et al., 2021).

This study investigates how humans modulate the contributions of feedforward and feedback control depending on task dynamics and uncertainty. Sixteen participants performed a pointing task using a wrist exoskeleton equipped with a force sensor, while surface electromyographic activity was recorded from flexors and extensors muscles. Participants first practiced a baseline condition without perturbation, followed by three conditions with mechanical perturbation at 30%, 60%, or 90% of movement amplitude (50% probability per block).

Consistent with theoretical predictions (Berret et al., 2024), muscle co-contraction and grip force increased in uncertain conditions compared to baseline, including in unperturbed trials. Furthermore, co-contraction increased as perturbations occurred closer to the target, indicating that humans adapt their co-contraction level to task demands. When the mechanical disturbance occurs late in the movement, feedback control is less effective due to inherent delays and noise, and the CNS increasingly relies on feedforward control.

Posters

Smoothness and performance in cervical head movements: validation of a higher-derivative mechanical model using the DidRen VR test

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Kinematic parameters provide valuable insight into sensorimotor control strategies during cervical movements. While simple outcomes such as movement duration are clinically accessible, more detailed kinematic variables, including movement smoothness, may reveal underlying motor control mechanisms. The DidRen VR test, a virtual-reality adaptation of a standardized cervical pointing task, enables controlled assessment of head movements while recording angular kinematics. Previous work showed that this test complies with Fitts' law and can be used to assess cervical sensorimotor performance (Dierick et al., 2024).

In the present study, we investigated whether a higher-derivative Pais–Uhlenbeck oscillator could account for kinematic features of voluntary head movements. This approach is grounded in recent theoretical work proposing that higher-derivative action principles may provide a relevant framework for modelling human motor control (White et al., 2025). Sixty-two healthy participants aged 18−25 years, free from neck pain and cybersickness, performed the DidRen VR test with targets arranged either horizontally or vertically. For each head movement, duration (T) and kinematic smoothness (log-dimensionless jerk, LDLJ), were computed from angular speed data recorded by the VR headset.

The experimentally observed relationship between T and LDLJ confirmed the parabolic link predicted by the higher-derivative model ($R^2 = 0.834$). Model parameters differed between horizontal and vertical movements, suggesting direction-dependent control strategies likely related to the distinct anatomical and biomechanical constraints involved in cervical rotation and flexion-extension. From a clinical perspective, these results suggest that a simple outcome such as T may reflect finer motor control features captured by movement smoothness.

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Thalamic Deep Brain Stimulation restores implicit motor adaptation in Essential Tremor

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Introduction Essential Tremor (ET) impairs sensorimotor adaptation and deep brain stimulation (DBS) of the ventral intermediate nucleus of the thalamus (VIM) exacerbates this deficit. However, because motor adaptation arises from the operation of multiple learning mechanisms, it remains unclear which mechanisms are disrupted by ET and DBS.

Our pre-registered study used two tasks, one that isolates implicit adaptation and the other that isolates explicit strategy use. We examined how ET and VIM-DBS impact these two learning processes.

We tested patients with ET (N=31) in DBS ON and DBS OFF conditions, along with age- and sex-matched healthy controls (N=32). We used a KINARM system to present the stimuli and collect kinematic data. To induce learning, we manipulated the position of a feedback cursor during reaching movements. Clamped feedback was used to isolate implicit adaptation and delayed feedback was used to isolate explicit strategy use.

ET patients showed reduced implicit adaptation compared to healthy controls when DBS was OFF. However, contrary to previous reports, turning DBS on restored, rather than disrupted, implicit adaptation. Notably, these recovery effects cannot be explained by DBS-induced tremor reduction. Explicit strategy use was not impacted by ET nor DBS.

DBS restored implicit adaptation in patients with ET while leaving explicit learning strategies intact. We will discuss potential circuit-level mechanisms through which thalamic DBS modulates sensorimotor adaptation and consider broader clinical implications of our findings.

Biomechanical and Reward Costs Influence on Decision-Making During Ongoing Actions

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Studies show humans prefer lower-cost movements in voluntary reaching, especially in decide-then-act contexts. It remains unclear if this applies to real-life situations where decisions occur during ongoing actions (decide-while-acting). Human movement decision-making is influenced by energetic costs and expected rewards. Biomechanical costs bias action selection, leading people to favor lower-effort options during ongoing reaching. However, real-world actions are driven by reward, not just effort. The interaction of effort costs and rewards during ongoing actions is still not well understood.

This study examined how reward and effort influence action selection during movement by investigating whether higher rewards can offset the costs of costly movements and alter target selection. Participants performed a reaching movement, deciding whether to continue tracking a target or switch to a new one, gradually deviating from the initial path. Biomechanical efforts were adjusted to create conditions with different motor costs. Targets also varied in reward to test cost–benefit integration during action.

Behavioral measures include target-selection frequency, reaction times, movement times, and changes of mind during actions. We expect a preference for less costly movements. Reward magnitude is hypothesized to influence this bias, leading participants to select more costly options with higher rewards. An interaction between reward and biomechanical cost is also anticipated, showing a dynamic cost-benefit process.

These findings advance models of embodied decision-making, showing online motor choices are influenced by biomechanical limits and effort costs. Understanding how the nervous system balances energy expenditure and expected outcomes offers insights into motor control, action selection, and adaptive behavior.

Influence of motor constraints in gaze decisions: evidence from individuals with oculomotor paralysis

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Orienting gaze is among the most frequent decisions that the brain makes. Saccade selection is shaped by several cognitive bottom-up and top-down factors. However, even when these factors are kept constant, gaze shifts are not equally likely in all directions. Typical observers have been shown to demonstrate a preference for cardinal movements over oblique movements. This cardinal-direction bias has been attributed to the greater neurocognitive complexity of programming oblique saccades, which requires the coordination of horizontal- and vertical-sensitive neural populations. In this study, we challenge this hypothesis by examining whether directional biases are also influenced by anticipated physical efforts.

We studied individuals with congenital horizontal oculomotor paralysis (Moebius syndrome, MS), who rely on head movements to shift gaze horizontally. Participants were presented with two targets and instructed to select one to look at. Typically developed participants demonstrated the anticipated cardinal bias. MS demonstrated a clear preference for vertical eye movements over horizontal gaze shifts. Critically, they preferred oblique gaze shifts, requiring coordinated short eye–head movements, over large horizontal head displacements. This finding indicates that directional biases are not exclusively determined by neurocognitive complexity but are also influenced by the anticipated physical costs. Movements involving larger, more effortful effectors may be disfavored, even when they are less demanding in terms of coordination.

The role of multimodal feedback during the learning of a rhythmic finger-tapping human–computer interaction task

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This study investigated how different sensory feedback modalities influence the acquisition and retention of a novel rhythmic finger-tapping task. Participants performed a human–computer interaction task in which they controlled a cursor using two keys on a computer keyboard. The combination and timing of key presses determined the cursor's planar movement direction and speed toward visual targets. Participants were randomly assigned to either a visual feedback group (V), which received only visual feedback, or a visual-auditory feedback group (VA), which received combined audiovisual feedback. In the VA condition, auditory feedback consisted of three proportional sounds, with tone, intensity, and frequency systematically mapped onto movement direction, cursor speed, and cursor–target distance.

Targets appeared randomly at predefined locations, equally spaced from a central starting point and distributed at 45° angular intervals. Participants were instructed to reach each target as quickly as possible using rhythmic finger tapping. The protocol consisted of 320 trials divided into eight blocks on Day 1, followed by a 40-trial retention block on Day 2 to assess learning retention. The VA group showed shorter movement path lengths but longer task completion times and more key presses than the V group. On Day 2, the VA group maintained initial performance levels comparable to the final block of Day 1, whereas the V group showed an initial performance decrement that was progressively recovered. Overall, these preliminary findings highlight the potential of multimodal feedback to support the acquisition and retention of novel rhythmic control skills in human–computer interaction.

Metacognitive insight into latent parameters of decision making

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Perceptual decisions are accompanied by metacognitive experiences, such as the sense of confidence, which closely follows the speed and accuracy of each decision. Confidence can shape subsequent decisions by prompting strategic adaptation of the decision-making process to improve performance. However, confidence can only inform a general sense of performance. Metacognitive insight into the setting of latent decision process parameters (such as bias and impulsivity) could improve strategic adaptation of decision-making compared to adaptation based on general confidence in a decision alone, by allowing decision-makers to pinpoint the source of an error and adapt accordingly.

We asked participants for subjective bias and impulsivity ratings after their decision on a random dot motion (RDM) task and used a hierarchical drift diffusion model (hDDM) to show that this rating is closely followed by trial-to-trial parameter estimates of drift bias and decision boundary. We concluded that individuals have metacognitive insight into these latent decision-making parameters, and next examined the informational sources that may underlie such insight. Subjective ratings may draw on task-related features—including stimulus, response time, and accuracy—and/or on readouts of physiological signals present during the decision-making process. In a follow-up experiment, we recorded electroencephalography (EEG) and pupil dilation during the RDM task. We will investigate the extent to which neurophysiological signals previously linked to drift bias contribute to subjective reports of bias. We expect to replicate previously found insight into bias, and to find that participants incorporate neurophysiological signals to inform their metacognitive assessments of bias.

Simultaneous sensorimotor control and contextual inference

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Interacting with our environment requires inferring task-relevant variables from sensory input and accounting for uncertainty in these inferences when controlling movements. Such inferences have been characterised across multiple modalities (perception, motor control, decision-making), but whether and how they occur simultaneously across modalities remains unknown. We studied interactions between two modalities at different levels of abstraction: low-level kinematic variables varying within individual movements, and abstract task context varying over trials.

Participants performed reaching movements in one of two task contexts (clockwise and counter-clockwise force fields). Prior information about task context was provided before each movement by the direction of a random dot motion stimulus, enabling systematic manipulation of prior contextual uncertainty. During movement, interacting with the force field potentially provided additional context information. We examined whether this information was used to update contextual inferences during movement, and whether these inferences fed back into sensorimotor control.

Our model combined two established models for performing kinematic state or task context inference in isolation: Kalman filtering within optimal feedback control, and a Bayesian model of contextual inference. We compared model variants differing in whether and how the two inference processes interacted during the movement. All variants reproduced identical movement trajectories in trials without contextual uncertainty. In trials with context uncertainty, variants with interactions between state and contextual inference during movement execution accounted better for movements in force field trials and for adaptation in channel trials. Our results suggest that sensorimotor and contextual inference are performed concurrently and interact at the timescale of ongoing movements.

Savings from repeated delay adaptation in target interception over multiple days

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Immersive virtual reality (VR) technology can induce visuomotor delays on top of the inherently occurring temporal mismatches between different sensory modalities. The spatial visuomotor adaptation literature showed behavioural benefits when re-exposing participants to specific perturbations (increased adaptation rates and decreasing aftereffects when removing the perturbation). Recent work from our lab suggests that these effects also occur for repeated delay adaptation within a single session. We here investigate behavioural effects of repeated delay adaptation over 8 separate days.

In each session, participants performed a VR target interception task consisting of three 90s blocks: 1. no cursor delay, 2. delayed cursor (333 ms), 3. no cursor delay, punching single approaching targets. After each block, participants synchronised their invisible hand with a horizontally moving target to measure participant’s point of subjective simultaneity (PSS).

Results show that the time point of maximum velocity (TMaxVel) of the interception movements for the first no delay block in each session is stable. During delay exposure, the timing of the actual hand movement shifted to earlier TMaxVel. The first trials after removing the delay in the last block show negative aftereffects for TMaxVel. Over multiple sessions, the adaptation rate increased, while the aftereffect in subsequent no delay blocks decreased, indicating savings even with exposures on separate days. The PSS stays distinct for both conditions with higher leads in the delay condition.

Taken together, our results indicate storage of two separate sensory feedback-action mappings for delay and no-delay conditions in a repeated interception task.

Tactile-Oculomotor Associations Reveal Reference Frame Scaling

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Localizing touch is fundamental to reacting to changes in our dynamic environment. Such localization requires encoding stimulus position relative to a landmark, which defines a reference frame. These frames are commonly assumed to be centered on specific body parts and are usually studied using explicit localization reports or stimulus-evoked potentials. Here, we introduce an innovative method to uncover reference frames and demonstrate that these frames are flexibly scaled to fit the stimulated area.

We recorded participants’ spontaneous oculomotor behavior following tactile stimulation of the fingers, with hands placed on either side of the body midline. When stimulating both hands, the left-to-right direction of gaze shifts reflected the left-to-right position of the hands relative to the body, consistent with a body-centered reference frame. In contrast, stimulating the right hand only revealed a hand-centered frame: stimulating fingers to the right of the middle finger elicited rightward gaze shifts, whereas stimulating fingers to the left elicited leftward shifts. Crucially, the middle finger was associated with a central gaze position despite the rightward location of the stimulated hand.

When stimuli were further restricted to the ring, middle, and little fingers, gaze shifts were centered on the ring finger, with stimulation of the middle finger inducing leftward gaze shifts and stimulation of the little finger resulting in rightward shifts. These findings challenge the idea that reference frames are centered on specific body parts and reveal that, instead, they dynamically scale to fit the stimulated area.

Continuous visual feedback increases the accuracy of our self-attribution of action outcomes

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Our sense of agency (SoA), the attribution of an action and its outcome to oneself versus external causes, is crucial for interacting with the environment. The SoA relies on predictions about sensory consequences of our actions based on efference copy, reafference, and forward models, distinguishing self-generated sensory signals from those triggered externally.

The formation of the SoA was previously proposed as a Bayesian observer model in which sensory observations of oneself and other agents are quantified as likelihoods. According to this model, the self-likelihood is largely determined by comparing sensory predictions and action outcomes. If this hypothesis were correct, the amount of sensory information should modulate the SoA.

We tested this by manipulating visual feedback in a virtual air hockey game, where participants performed goal-directed movements to hit a puck toward a target. Another, unseen agent could perturb players' actions, creating an alternative contribution to the action outcome. The puck trajectory was either shown continuously or was Invisible. In different experiment phases, participants hit specific targets, predicted their or the other agent's outcomes, or judged their SoA.

Our data show that SoA judgments are most consistent for unperturbed movements and decrease with increasing perturbations by the other agent. Importantly, more visible feedback about the puck trajectory improved prediction accuracy and also modulated the SoA judgments.

Our results suggest that additional sensory feedback changed the self-likelihood function and increased self-attribution accuracy, supporting the Bayesian observer model for the mechanisms underlying the SoA.

Pain perception of electrocutaneous stimuli is influenced by their intensity sequence

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Perception is influenced by the intensity sequence of a stimulus, e.g., by brightness in the Craik-O'Brien-Cornsweet illusion or by loudness in the Rawdon-Smith illusion. Here, we ask if the temporal order of stimulus intensity affects the resulting pain perception.

To elicit pain, we use electrocutaneous stimulation near the wrist of the non-dominant hand. All stimulus sequences last for 8 seconds, and their intensity is the same for the 2 seconds at the beginning and at the end of the sequence. During the 4 seconds in the middle of the sequence, stimulus intensity is split into three conditions: a) falling-then-rising intensity, b) rising-then-falling intensity, i.e., the reverse sequence of condition a), c) no change, i.e., constant intensity. Each stimulus condition is repeated 8 times per participant in pseudo-random order. Participants use two visual analog scales to rate their perceived pain during the first and the last 2 seconds of a stimulus sequence, while ignoring the 4 seconds in the middle, as indicated by a lamp. We analyze the second rating of a stimulus relative to its first, to eliminate effects across stimuli.

Based on pilot data (n=8), the stimulus conditions may influence the perception of pain. Relative to the constant condition, the rising-then-falling sequence lead to a pain reduction, and the falling-then-rising sequence lead to a pain increase. This appears consistent with visual and auditory illusions that are elicited by similar stimulus manipulations, suggesting a general sensory phenomenon.

To thoroughly test the existence of the pain modulation, we pre-registered the study https://doi.org/10.17605/OSF.IO/JAZ48.

Addressing sensorimotor information flow between the kinematics of throwers and catchers in an overarm ball throwing experiment

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Interception of a moving object is among the fundamental human sensorimotor skills that requires the ability to perform predictions. In the case of objects thrown by another human, as, for example, in interceptive sports, predictions can rely on both the object's trajectory and the anticipatory cues provided by the motion of the thrower. Here we address the information flow between the kinematics of throwers and catchers in an overarm ball throwing-and-catching experiment. The analysis relies on information-theoretical tools applied to the recorded positions of markers placed on 18 joints of the participants' bodies, as well as of the ball flight parameters. We show that the information shared by throwers' and catchers' kinematics is only partially—and redundantly—accounted for by the ball flight parameters: a residual, ball-independent information shared between the two kinematics is present, mostly in the time interval before and around the instant at which the ball is released. Furthermore, the joints for which such shared information is significant include contralateral ones, whose motion turns out to be a relevant carrier of prediction cues. These results provide evidence that the movement of catchers, although primarily based on the observation of the ball flight trajectory in the later phases, in the anticipatory phases significantly relies on the observation of the thrower, in a non-trivial way.

Contribution of axial and shear fingertip strains on haptic force control

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Skin deformation at the finger-object contact interface conveys information used to ensure a secure grip. High-resolution imaging has shown that partial slips at the fingertip form distinct patterns during finger loading. These patterns are combinations of stretch, compression, and shear. However, the contribution of these local axial and shear strains in online force control remains an open question. To investigate this, we independently manipulated axial and shear strains at the finger-object contact while participants applied a voluntary tangential force, amplifying or reducing the strains at contact using a tactile display. We found that amplifying axial strains in the periphery of the fingertip contact area leads to a reduction in applied tangential force, while normal forces remained unchanged. In contrast, manipulating shear strains did not significantly affect the applied forces. These findings suggest that axial strains within the contact area are used as feedback in haptic sensorimotor control and inform the development of more efficient haptic devices.

Climbing through affordance landscapes: a computational model of sequential motor planning

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Planning sequences of actions in dynamic, physically constrained environments requires the integration of perceptual, cognitive, and motor skills. Sport climbing offers a principled testbed for studying such embodied decision-making, as climbers must select successive moves from a continuously evolving set of options under biomechanical constraints. Here we present a computational model of a virtual climbing agent that solves problems on the standardized climbing wall (the MoonBoard) by navigating a data-driven affordance landscape. The landscape is defined as the product of four independent components — encoding hold graspability, body pose plausibility, move reachability, and proximity to the goal — each learned from a dataset of 381 annotated solutions. Action selection combines greedy landscape-guided choices with a Monte Carlo look-ahead planner that evaluates trajectories and selects moves based on their overall cost. The affordance landscape formulation allows for ablation studies that reveal the relative role of different perceptual and motor skills. Ablations in the look-ahead selection of optimal strategy allows instead to assess how planning skills shape performance. As a result we find that the pose component, which implicitly captures biomechanical constraints, contributes most to performance, while planning depth of four steps substantially outperforms shorter-sighted planning strategies. The model provides a transparent, interpretable account of climbing behavior and illustrates how affordance-based frameworks can guide sequential motor planning in complex, naturalistic tasks.

The impact of Essential Tremor on strategic motor adaptation

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Essential tremor (ET) is a highly prevalent movement disorder that introduces substantial noise on goal-directed movements. This could impair the ability of patients to detect and correct systematic movement errors. While ET is known to impair overall motor adaptation (Chen et al., 2006), it remains unclear whether this reflects a deficit in implicit, automatic adaptation, the utilization of a deliberate re-aiming strategy, or a combination of both. This study examines whether ET specifically impairs the development of a re-aiming strategy.

In two experiments, patients with ET and age- and gender-matched controls will perform reaching movements using a KINARM end-point lab.

In the first experiment, visual feedback of the hand position will be perturbed by a gradual visuomotor rotation (1.5° every movement cycle, ramping up to 60°), delayed by 800 ms to minimize implicit feedback. We expect patients with ET to require larger perturbations than controls before implementing a re-aiming strategy.

In a second experiment, we examine whether a higher threshold in detecting visuomotor errors causes this delay in launching a re-aiming strategy. Visuomotor rotations of varying angles across movements will be imposed, while participants judge whether the visual feedback was perturbed. We expect an elevated detection threshold related to movement variability in patients with ET.

This ongoing study will clarify whether impaired motor adaptation in ET is partly due to a relative inability to identify movement errors that could be corrected by deliberately adjusting movement planning – with potential implications for the capacity for everyday motor learning in ET.

Parallel Planning of Motor Sequences: Effects of Planning Depth on Competitive Queuing

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Skilled behaviour depends on the ability to prepare multiple actions in the correct order before movement execution. Previous MEG work by Kornysheva et al. (2019) identified a competitive-queuing (CQ) gradient during preparation of learned motor sequences, whereby neural representations of upcoming sequence elements are activated in parallel according to their serial position. More recently, Karagiorgis et al. (2026, under review) reported CQ gradients not only during motor sequence preparation but also during passive listening to learned tone sequences, suggesting that CQ may reflect a domain-general mechanism for serial-order representation.
In this study, we investigated whether the CQ gradient is sensitive to the planning depth of upcoming motor sequences. Seventeen healthy adults performed previously trained finger sequences during MEG recording. Sequences varied in length (1-, 3-, and 5-element sequences) and included both multi-finger and repeated-finger patterns. Multivariate linear discriminant analysis classifiers were trained on neural activity associated with 5-element sequences and tested on preparatory neural activity preceding sequences of different lengths.
This approach allowed us to assess whether CQ-related neural dynamics vary as a function of the number of upcoming actions. We will present preliminary analyses characterising preparatory decoding patterns across sequence types and discuss their implications for competitive-queuing accounts of sequential planning.

Proprioception and Aging: Does action or perception tell the full story?

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Proprioception (our sense of body position and movement) is considered to decline with age, yet behavioral findings remain inconsistent. A major contributor is how proprioception is assessed: current measures require conscious verbal report of limb position following passive movement, which differs from everyday function, where proprioceptive signals are integrated unconsciously to guide ongoing actions. The present study addresses this gap by introducing an approach based on motor performance (action-based tasks) rather than explicit perceptual judgments (perception-based tasks), offering more ecologically valid and potentially more sensitive measures. Two robotic-based tasks were administered: a perceptual boundary task and its active equivalent, the perturbation task. Both required participants to reach toward a target while a manipulandum deviated the hand mid-movement across varying magnitudes. In the perception-based version, participants verbally reported whether their hand was left or right of the target at movement's end. In the action-based version, participants reached toward the target while we measured the corrective force applied against the deviation. A large sample of young and older adults (n = 60 per group) completed both tasks. No age-related differences were found in either measure. However,
performance on the two tasks was uncorrelated and differed significantly at the population level, suggesting they capture distinct aspects of proprioceptive function. Despite involving identical movements, action-based and perception-based tasks do not appear to measure the same construct, underscoring the importance of task selection in proprioceptive assessment and raising fundamental questions about what each approach truly captures.

Cerebellar and parietal contributions to recalibration of perceived agency: a TMS study

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Sense of agency refers to the subjective experience of controlling sensory outcomes through one's own actions and is central to maintaining a coherent sense of self and of the external world. Although actions and their outcomes must be temporally aligned for agency to arise, agency can be maintained despite temporal delays through recalibration processes, allowing efficient compensation for sensorimotor delays. Evidence implicates the inferior parietal lobule (IPL) and the cerebellum in agency attribution; however, their role in agency recalibration remains unclear. Here, we investigated whether disrupting activity in the IPL or cerebellum interferes with the recalibration of perceived agency. The final sample consisted of 42 right-handed participants with no history of neurological or psychiatric disorders. Participants completed a three-day experiment involving stimulation of the right IPL, cerebellum, or vertex (control site). On each day, participants pressed a button that triggered the presentation of a Gabor patch and subsequently made agency judgments for action–outcome pairs with variable response–stimulus asynchronies (RSAs). Following this baseline measure, repetitive TMS (200 bursts of 3 pulses at 30 Hz) was applied over the right IPL, cerebellum, or vertex. Participants then completed an adaptation phase in which button press–Gabor patch pairs were presented with a 150 ms delay, followed by agency judgments with variable RSAs. Results showed recalibration of agency following adaptation. However, we found no evidence that TMS-induced interference over the IPL or cerebellum affected this recalibration. These findings challenge a causal role of IPL and cerebellum in the recalibration of perceived agency.

From perceptual decision confidence to sensorimotor confidence

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Bayes optimal perceptual decision making requires accounting for sensory uncertainty as it can change the decision boundary needed when making decisions. Similarly, our subjective sense in the quality (confidence) of our decisions is guided by both incoming sensory input (how far from the decision boundary is it) and the uncertainty in this input. However, task performance (and our subjective estimate of it) in a sensorimotor task (e.g. driving) requires incorporating sensory noise (e.g. where am I relative to other vehicles), motor execution noise (did I steer to get the correct vehicle motion), noise in our predictions (how will the vehicle steer, how will other road users behave) and internal model, as well as uncertainty in the dynamics of the environment (different road types, vehicle dynamics). Here we formalize this idea using stochastic optimal control and the resulting expected loss to generalize the notion of perceptual decision confidence to sensorimotor confidence. In addition, we begin to probe the predictions of this formalization using a simplified motor task (skittles) where observers must hit a target by ballistically colliding with a ball and provide a confidence measure of hitting the target. Specifically, we manipulated the quality of sensory information the trajectory provides as well as the dynamics (ball mass). Consistent with predictions we found higher confidence when quality of sensory information was high and lower confidence with higher ball mass (as it lowered task performance), in all cases confidence tracked task error.

Uncovering interpersonal and intertask variability of muscle synergies with demixed PCA

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The control of gait requires the simultaneous contraction and relaxation of many different muscles. This complex motor coordination task can be better understood by focusing on groups of muscles that change in a synchronised way, named muscle synergies, instead of individual muscle dynamics. How muscle synergy recruitment changes as a function of the motor task and of the person engaged in it is an active research area.
Muscle synergies are obtained by applying dimensionality reduction techniques like principal component analysis (PCA) or non-negative matrix factorisation (NMF) on electromyographic recordings. These methods have been successfully applied to study a single walking condition. However, no two ways of walking are equal: muscle coordination patterns, and thus muscle synergies, vary when changing walking conditions (e.g. inclination, speed, evenness) or the physical characteristics of the walker (e.g. limb length, strength, flexibility). Traditional tools of synergy analysis such as PCA and NMF are incapable of capturing this variance across subjects and conditions.
Recently, demixed PCA (dPCA) has been introduced to cognitive neuroscience to separate sources of variance and study them independently. Applied to electromyographic data, it enables a better understanding of how muscle coordination patterns are modulated by parameters of the motor task and how they vary across different subjects. The resulting analysis reveals that muscle activation patterns undergo abrupt changes at critical values of the task parameters. Similarly, for fixed task parameters, our analysis maps clusters of the measured subjects into well differentiated groups of similar walkers.

How do growth-related biomechanical changes shape the requirements and organization of spinal control during human locomotor development?

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Human locomotor development arises from the interaction between neural control and a rapidly changing musculoskeletal system during early stage of life. Although spinal locomotion is commonly described as the result of central pattern generators (CPGs) interacting with sensory-driven reflex pathways, the respective contributions of these components and how their interaction evolves during growth, remain poorly understood. Direct experimental investigation of human spinal circuits, particularly in infants and young children, is inherently limited, motivating the use of neuromechanical modeling as an integrative approach.

The present research project aims to investigate how growth-related biomechanical changes shape the organization and requirements of spinal control during human locomotor development. We employ a physiologically plausible neuromechanical framework combining CPG-based rhythmic control with reflex-mediated sensory feedback to study the emergence and adaptation of locomotion as musculoskeletal dynamics evolves. By progressively adapting the model to developmental changes in limb length, mass distribution, muscle strength, tendon properties, and so on, we seek to understand which aspects of locomotor development can be explained by biomechanics alone and which require adjustments in spinal control parameters.

Specifically, this work addresses three interconnected questions: (1) how biomechanical growth influences the stability and performance of spinal locomotor control; (2) how reflex gains, delays, and sensory feedback must adapt to maintain stable locomotion as morphology changes. By systematically exploring the interaction between neural control and biomechanics, this research aims to provide a unified framework for understanding the emergence of adult-like locomotion from early, immature motor behaviors.

Planning Horizon of Sequential Reaching Movements depends on Target Configuration

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In sequential actions, humans often choose movements that are suboptimal for the present action in order to secure better options for future actions. The benefit of such forward planning depends on the nature of the task, but whether humans dynamically adjust their planning horizon to task demands is unknown. In this study, participants performed a fast sequential reaching task where they had to reach for as many targets as possible within a limited time period of 2.3 to 2.8s. This time constraint incentivises minimising the movement distance between sequential targets. Trials of sequential reaches were made within a configuration of 14 targets that were either distributed homogeneously or cluttered across either a small (25 by 15 cm) or large (40 by 24 cm) workspace. Participants collected on average 6-8 targets during each trial. We fit optimal planning models with various planning horizons based on the participants' target choices. This revealed that participants shifted to a longer planning horizon with cluttered target configurations, particularly in the large workspace. We conclude that planning ahead is more beneficial for minimising distance in a cluttered environment. Thus, humans are capable of adjusting their planning horizon for fast sequential reaching movements according to the configuration of targets.

Assessing gait control from short time series using a geometric characterization of stride-by-stride corrections

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Gait variability in healthy adults exhibits Long-Range Autocorrelations (LRA), meaning that the fluctuation at any time statistically depends on previous gait cycles. Previous studies have interpreted LRA within an optimal control framework, where stride length and duration are regulated in a coordinated manner to maintain a constant walking speed. Such objective offers redundancy in the set of gait parameters that achieve success. In this context, imposing constraints on the walking cadence reduces this redundancy and leads to a loss of LRA. The model therefore makes a clear prediction that has remained unexplored: during free walking, stride-by-stride adjustments should be directed toward the redundant axis, whereas during cued walking, they should be directed toward the imposed target values. Consequently, differences between conditions should be observable based on a geometric characterization of changes in length and duration, in addition to traditional analyses of LRA. Based on simulations and experimental data, we show that stride-by-stride adjustments can discriminate cued and free walking conditions, providing direct support to the geometric interpretation of the model. Moreover, this metric achieved good discrimination (Area Under Curve, AUC=0.74) for series of 50 strides, while estimates of LRA were less reliable with such short series (AUC=0.60). Finally, we quantified how much these estimates depended on the presence of an initial asynchrony between the onset of rhythmic cues and the subsequent stride. Overall, our study validates a novel geometric approach to quantify gait control strategies, which supports the emergence of LRA as a result of flexible adjustments of gait control.

Sensory attenuation in patients with Essential Tremor

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Essential Tremor (ET) is a neurodegenerative disorder marked by involuntary oscillations during voluntary movements, primarily affecting the upper limbs. Delays in feedback control systems can induce such oscillations if uncompensated. In upper limb control, delay compensation relies on long-latency pathways involving the cerebellum and somatosensory areas. We hypothesized that ET patients exhibit inaccurate delay compensation in these pathways, supported by simulations and experimental studies.
A key aspect of delay processing is sensory attenuation, where self-generated forces are perceived as less intense than externally applied ones. This relies on tactile predictions synchronized with movement via efference copy. Healthy individuals adapt to delayed self-generated touches after repeated exposure. We investigated whether sensory attenuation is preserved or impaired in ET patients, suggesting disrupted internal delay processing.
23 ET patients and matched controls participated. They received two taps on their left finger: one self-generated and one externally delivered. Exposure trials introduced delays (0 or 100 ms) between the active tap and the second tap, resulting in four conditions. A control condition (both taps external) was included. Participants compared tap intensity. Clinical assessments (FTM scale, accelerometer-based kinematics) were conducted.
FTM scores correlated with power spectral density. While resting tremor showed no group differences, postural tremor was greater in patients. Both groups exhibited sensory attenuation in the [0–0 ms] condition, but patients failed to adapt to the [100–100 ms] delay, showing reduced attenuation compared to controls. ET patients retain sensory attenuation but struggle to adapt to delayed feedback, indicating impaired internal delay processing.

Impact of sensorimotor delays on the dimensionality of a network model of state estimation

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During movement execution, the brain compensates for sensorimotor delays by computing an estimate of the current limb state from delayed sensory feedback and internal motor predictions. While optimal feedback control theory performs this computation through the Kalman filter, the neural mechanisms supporting accurate state estimation remain unclear. In this study, we trained recurrent neural networks (RNNs) to replicate the output of a Kalman filter across biologically plausible delays (0–120 ms) and two biomechanical configurations (one and two degrees of freedom), using data generated from a Linear Quadratic Gaussian controller simulating human reaching movements.
Analysis of the trained networks revealed a dissociation between connectivity structure and network dynamics. While the effective rank of the recurrent connectivity matrix remained stable across delays, the effective rank of the activity covariance matrix increased with delay, indicating that longer delays require richer neural dynamics despite similar structural complexity. Principal component analysis of network activity confirmed that trajectories occupy higher-dimensional spaces as the delay increases.
Further analysis of network dynamics revealed two distinct computational regimes. Short delays induced strongly non-normal connectivity, associated with transient amplification of neural activity — a strategy that rapidly projects the internal state estimate forward in time. Conversely, long delays produced more normal connectivity with weaker amplification and slower, more stable dynamics consistent with active state maintenance.
These results challenge the prevailing emphasis on low-dimensional neural trajectories in motor control, and suggest that sensorimotor delay compensation requires higher-dimensional dynamics whose structure reflects the computational demands imposed by the delay.

Interlimb exploration: when one hand fails, the other hand explores

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Exploration, defined as varying movements in response to failure is a key component of reward-based motor learning. Exploration is most commonly studied by assessing trial-to-trial changes in movement attempts made by the same limb. However, it remains uninvestigated whether exploration is a single limb process, or whether failure in one limb may also lead to exploration when followed by a movement attempt with the contralateral limb (i.e. whether "interlimb exploration" occurs). When performing a targeted movement, two types of exploration may manifest 1) motor exploration (i.e. exploration of "how" to perform the movement, and/or 2) target exploration (i.e. exploration of "what" the movement should target). Originally, exploration has been conceived as motor exploration. However, we hypothesize that target exploration exists and, due to its limb-independent nature, will present itself as interlimb exploration. We tested the prediction that failure feedback following movement of one hand increases trial-to-trial variability in the motor output of the other hand. In a force-control-task participants propelled marbles to find the target force that would result in reward feedback. The landing position of the marble was hidden by a curtain. Thirty-four participants completed two conditions: a single-limb condition (same hand used for 50 trials, then switched) and an interlimb condition (alternating hands every trial). Binary feedback (success/failure) was provided based on a random list defining 20 trials as successes and 80 as failures. Significant exploration was observed in both conditions, consistent with target exploration. These results suggest that exploration can be a shared process between limbs.

Does Increased Demands for Online Correction Enhance Motor Adaptation?

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Classical theories of motor adaptation propose that larger corrective responses lead to stronger motor learning. To test this prediction, we manipulated the demand for online correction while exposing participants to a standard adaptation task. Participants performed reaching movements in a velocity-dependent force field toward either square or rectangular targets. Square targets imposed stricter lateral accuracy requirements at the end of the movement and elicited stronger corrective responses, whereas rectangular targets allowed lateral deviations and reduced correction demands. Two groups (n=18 per group) experienced different proportions of square and rectangular targets during force-field adaptation: one group had a majority of square targets, whereas the other group had a majority of rectangular targets. Their performance was then assessed based on trials towards the square targets and based on catch-trials with similar statistical distributions. Contrary to the classical prediction, both groups exhibited similar adaptation across trials, with comparable learning rates, steady-state performance, and catch-trial aftereffects, despite the fact that participants exposed to a large number of rectangle targets had generally reduced feedback corrections. These preliminary findings suggest that increasing the requirement for online corrective responses alone may not be sufficient to enhance motor adaptation.

Transcutaneous auricular vagus nerve stimulation and reward shape reflex responses during reaching movements

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Feedback responses during reaching movements, short-latency (SL, [20–50] ms post-perturbation) and long-latency (LL, [50–100] ms), are mediated by spinal and supraspinal circuits, respectively. The LL component adapts to task demands, scaling with precision requirements (e.g., larger for narrow targets, smaller for wide ones). While these mechanisms are well-established, their neural regulation remains unclear. Arousal, a key modulator of the central nervous system, may play a critical role. Two interconnected systems contribute to this process: the substantia nigra–dopaminergic system, which invigorates movement and enhances feedback responses independently of task goals, and the locus coeruleus–norepinephrine system, which we recently showed to refine task-dependent feedback modulation via transcutaneous auricular vagus nerve stimulation (taVNS). However, their combined influence on feedback responses is unknown.

To investigate this, 24 right-handed participants performed reaching movements toward narrow or wide targets, with 4 seconds sham or active taVNS stimulation prior to the movement onset. Trials included a reward pre-cue (50-cent incentive for success) or no reward, randomized and presented during stimulation. Mechanical perturbations (67% of trials) elicited reflex responses in the right Posterior Deltoid or Pectoralis Major, recorded alongside kinematics, pupil size (arousal index), and behavioral performance.

Preliminary results confirm expected SL and LL responses, with LL components larger for narrow targets. Reward tended to increase deltoid feedback responses, while active taVNS showed a trend toward reducing LL responses. These findings suggest distinct roles for reward and taVNS in modulation of feedback responses.

Adaptive Feedback Control as Model of Motor Learning Strategies

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Humans rapidly adapt reaching movements to predictable environmental disturbances, yet the computational mechanisms supporting this flexibility remain incompletely understood. Most previous studies have characterized this adaptation through trial-by-trial updates of discrete variables. However, such representations may not be explicitly available to the nervous system, leaving the underlying learning mechanism unresolved. Recently, adaptive feedback control approaches have been introduced that instead consider continuous variables and plausible learning rules, but have so far been limited to simplified linear limb models. Here, we investigate whether this framework can predict motor adaptation patterns when coupled with realistic upper-limb biomechanics. The proposed model combines a continuous online least-squares learning algorithm with state-feedback control, allowing the controller to identify and compensate for external disturbances during movement. We evaluate the model's ability to capture trial-by-trial adaptation to external perturbations. To further characterize the capabilities of the model beyond pure computational analyses, we compared its predictions with human learning trajectories in a reaching task under ambiguous load nature reported by Singh and Scott (2003). Our model was able to predict the gradual reduction of movement errors and an inability to generalize perturbed dynamics. We therefore show that this framework, previously limited to linear settings, can also predict human behavior while accounting for realistic limb biomechanics. Together, these results establish adaptive feedback control as a computational framework for testing hypotheses about the neural implementation of sensorimotor adaptation and its interaction with online control.

Planning Horizon of Sequential Reaching Movements depends on Target Configuration

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In sequential actions, humans often choose movements that are suboptimal for the present action in order to secure better options for future actions. The benefit of such forward planning depends on the nature of the task, but whether humans dynamically adjust their planning horizon to task demands is unknown. In this study, participants performed a fast sequential reaching task where they had to reach for as many targets as possible within a limited time period of 2.3 to 2.8s. This time constraint incentivises minimising the movement distance between sequential targets. Trials of sequential reaches were made within a configuration of 14 targets that were either distributed homogeneously or cluttered across either a small (25 by 15 cm) or large (40 by 24 cm) workspace. Participants collected on average 6-8 targets during each trial. We fit optimal planning models with various planning horizons based on the participants' target choices. This revealed that participants shifted to a longer planning horizon with cluttered target configurations, particularly in the large workspace. We conclude that planning ahead is more beneficial for minimising distance in a cluttered environment. Thus, humans are capable of adjusting their planning horizon for fast sequential reaching movements according to the configuration of targets.