Karlsruhe Institute of Technology

10th World Congress of Biomechanics
JULY 11 – 15, 2026 I VANCOUVER, CANADA

IPEK
Institute of Product Engineering
at Karlsruhe Institute of Technology

A Multimodal Measurement Approach for Analyzing and Characterizing Shaking Dynamics in Shaken Baby Syndrome Using Optical Motion Tracking, Accelerometers, and Force-Sensing Films with Offender-Profile-Aligned Participant Sampling

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Introduction

Shaken Baby Syndrome

- Shaken Baby Syndrome (SBS) is considered a subtype of **Abusive Head Trauma** (AHT) in which the injuries are primarily caused by **violent shaking**.
- AHT is one of the **most common non-natural causes of death** in infants and young children during the first two years of life. With a reported **mortality rate** of **13–36 %**, while **62–96 %** of survivors suffer **long-term neurological impairments**. [1]

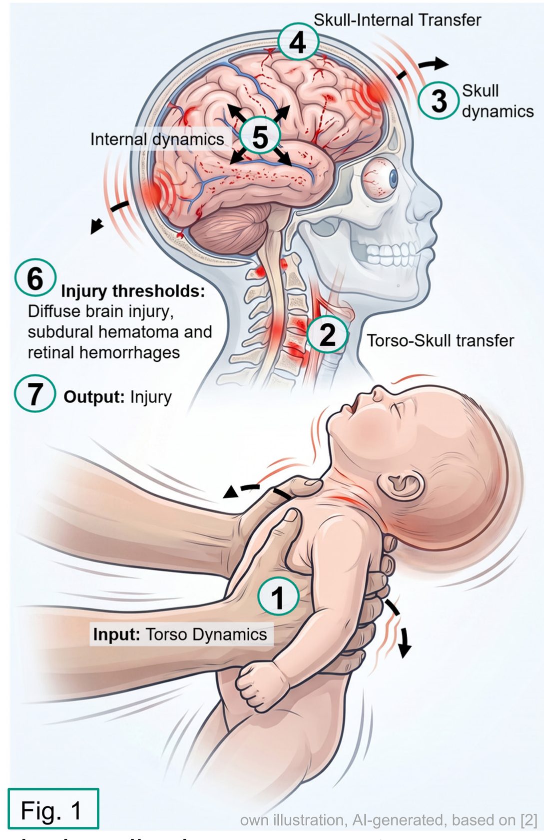

Fig. 1

- The **pathogenesis** is described as a seven-step sequence of events leading to the characteristic **injury triad** (Fig. 1), acute brain injury (encephalopathy), subdural hematoma, and retinal hemorrhages, while additional injuries, such as cervical spine injuries [2], rib fractures, long-bone fractures, and soft-tissue hematomas may also occur.
- For biomechanical model development and validation, whether for physical anthropomorphic test devices (ATDs), finite element or rigid body simulations, the **applied load case** is a **key factor** [3].
- It has been shown that **infant head kinematics** are **highly sensitive to** the **characteristics** of the **imposed shaking motion**, while being comparatively insensitive to model parameters describing the mechanical properties of the head and cervical spine, suggesting that future work should focus more on refining the loading input rather than material properties [4], although this remains an ongoing subject of scientific discussion.
- Whereas previous trajectory studies have primarily examined the biomechanical response of ATDs, even though their limited biofidelity [3] and the use of participant samples with ages deviating from typical offender profiles may constrain transferability, this study focuses on the **excitation** of the ATD through **offender-profile-aligned participant sampling**, together with the way the ATD is **held** and the **resulting hand forces**.
- This study explores the added value of a **multimodal measurement approach** by combining different sensor concepts **for within-method triangulation** and integrating quantitative sensor data with participant observation for **between-method triangulation**, thereby enhancing the credibility and robustness of the measured trajectories.

Research Questions

- How is the ATD **held** during shaking?
- What **hand forces** do participants within the typical offender-age range generate during shaking?
- Which **trajectories** and **shaking frequencies** are achieved by participants within the offender-age range?
- Is within- and between-method triangulation beneficial for improving credibility in collected motion data?

Methods

Setup

- A positive ethics and data protection approval was obtained prior to study commencement and all data were anonymized before analysis.
- A nine-camera **Vicon motion capture system** (Fig. 2–4, yellow frame) was used for 3D tracking of participants, with data processed in Vicon Tracker 3.9 (Vicon Motion Systems Ltd., Oxford, UK). Reflective marker clusters were attached to participants' elbows and hands, and an additional cluster was mounted on the back of the ATD (**RealCare Shaken Baby**, 3.1 kg, 51 cm). The ATD head was covered to avoid optical interference. For redundancy and independent tracking, two Basler cameras (acA1300-200uc; Fig. 2, orange frame) were used, together with **ArUco markers** (Fig. 3-4, red frame) on the participant's right arm, hand, and ATD back. Intrinsic and extrinsic camera calibration was performed using a ChArUco board.
- A **tri-axial accelerometer** (PCB Piezotronics Model 356A03; Fig. 3, green frame) mounted on the ATD back recorded dynamic accelerations during shaking, with signal conditioning via a charge amplifier (PCB 482C05) and analog-to-digital conversion using an NI USB-6008. **Hand–dummy interaction forces** were measured using a TekScan Pressure Mapping Sensor 4256E (Fig. 4, purple frame), attached to disposable gloves on both hands, capturing pressure distributions of fingers & palm.
- Data were processed using custom Python scripts, with synchronized multi-sensor acquisition enabling triangulation across motion capture, optical tracking, acceleration, and force measurements.
- **Participant behavior** was additionally documented by two independent observers, including grip strategies, handling patterns, movement styles, and technical anomalies.

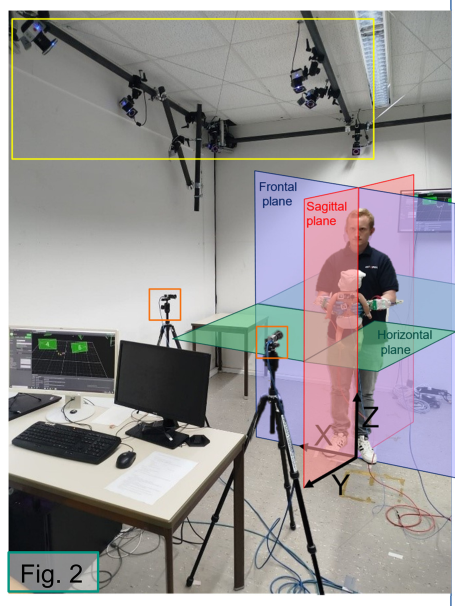
Fig. 2

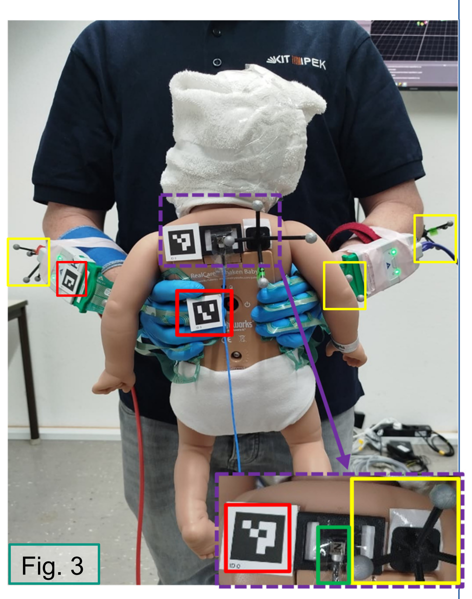
Fig. 3

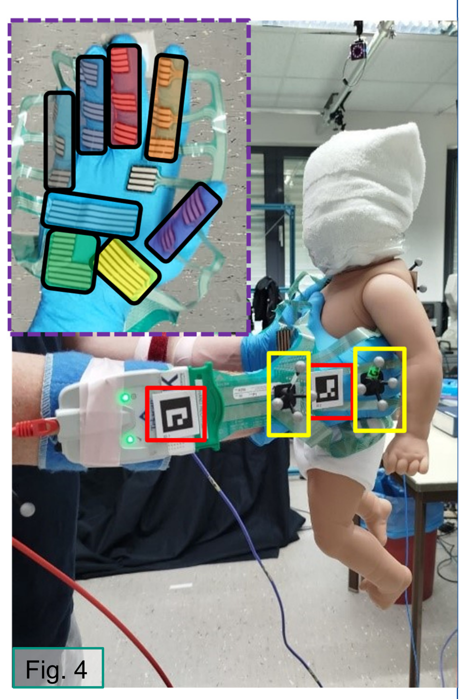
Fig. 4

Study

- Participation was voluntary and could be withdrawn at any time.
- Study included **15 healthy volunteers**, the target population was aligned with the offender profile described in the literature, with an intended age range of 18–35 years; final sample ranged from **21–35 years**.
- A sex distribution of **60% male participants** was targeted to approximate the sex distribution reported for offenders in AHT cases.
- **Exclusion** and **withdrawal criteria** were assessed (e.g. psychological preconditions, relevant physical impairments, as well as a history of miscarriage).
- Participants signed the data protection document and completed the **standardized questionnaire** (**demographic**, **anthropometric**, and **functional baseline data**).
- The sensors were then attached and the setup was connected
- Participants were instructed to shake the ATD **as quickly and forcefully as possible** for about **10 seconds**, as if **under extreme stress**, while **participant observation** was conducted in parallel. This procedure was **repeated three times** per participant.
- Afterward, each participant took part in a short debriefing and received contact details for the study team.

Results & Conclusions

Trajectory and Frequency

- The accelerometer measured an average **shaking frequency** of **5.5 Hz**.
- **Four recurring trajectory patterns** were identified (Fig. 5–8) and categorized by visual inspection of spatiotemporal movement patterns. Group assignment was performed via expert-based qualitative clustering of similar trajectory shapes, and cross-validated using ArUco data.
- The green line (Fig. 5-8, Vicon dataset) shows the mean value across all subjects with a similar shaking pattern. The error bars represent the simple standard deviation (± 1σ) and are plotted at every fifth time step, corresponding to a distance of 50 ms at a sampling rate of 100 Hz for clarity.
- **Trajectory 1** (Fig. 5) was **observed** in 8 of 15 participants and was **most** frequently followed by **Trajectory 2** (Fig. 6) in 5 of 15 participants, while one participant initially performed shaking similar to Trajectory 1 in the first two trials and then switched to Trajectory 2.
- The ArUco- and Vicon-based trajectory measurements provided **mutual validation** by independently capturing the same trajectories. Temporary tracking losses caused by marker occlusion in one system were compensated for by complementary measurements from the other system.
- All participants predominantly moved in sagittal plane, with X-axis displacements remaining <10 mm.
- Fourteen participants lifted the ATD from an approximately hip-height cradle using both **hands placed on the thorax** (Fig. 3), while one female participant initially grasped the ATD by the arms and subsequently regripped the thorax immediately before initiating the shaking motion.

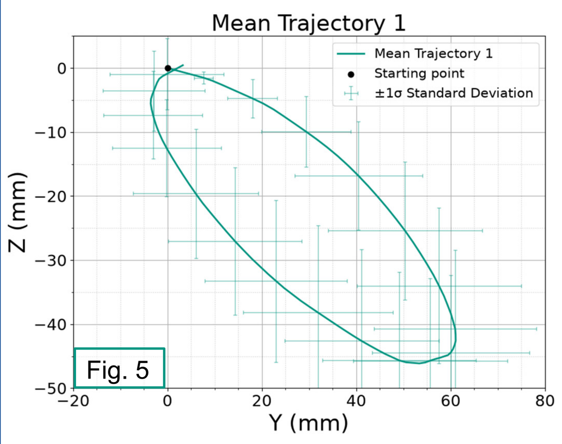

Fig. 5

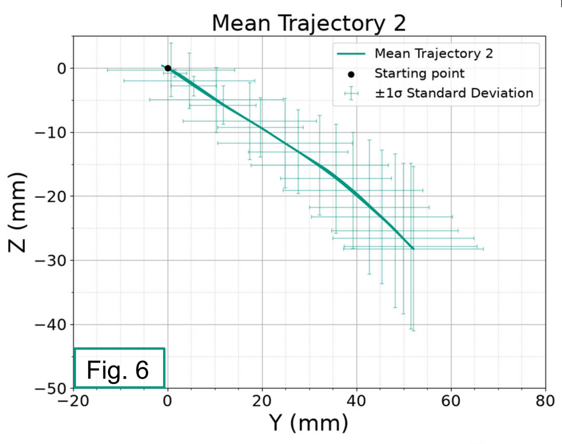

Fig. 6

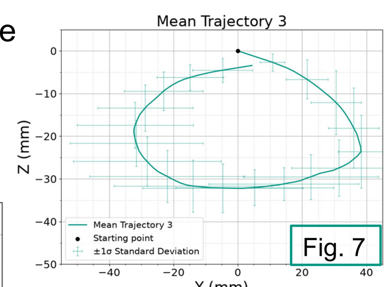

Fig. 7

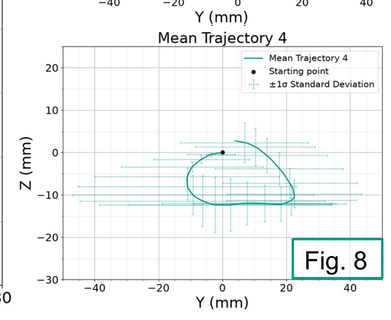

Fig. 8

Hand Forces

- Fig. 9 shows the **mean pressure across all participants** for the right hand, while Fig. 10 presents the mean pressure of an exemplary male participant (colored outline indicates the sensor regions corresponding to the purple area of Fig. 4).
- The **fingertips** exhibited the **highest force values** across participants.
- The palm also showed elevated pressure levels, although not consistently across all participants.
- Some participants showed a wave-like alternation between palm/thumb and fingertip loading.
- No clear correlations with the other measurement systems were identified.
- **No significant differences between sexes** were observed; however, participants with regular strength training tended to apply higher grip forces.

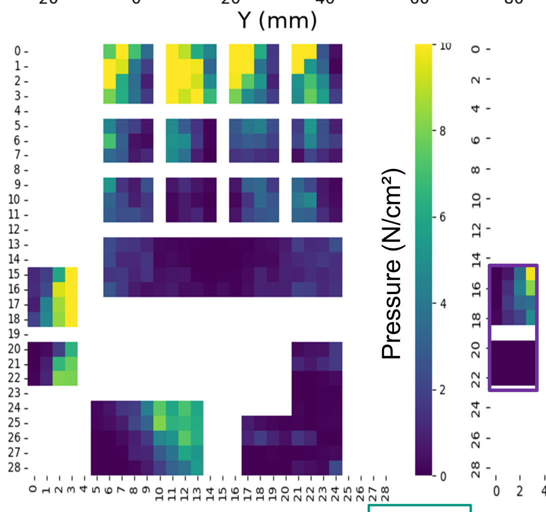

Fig. 9

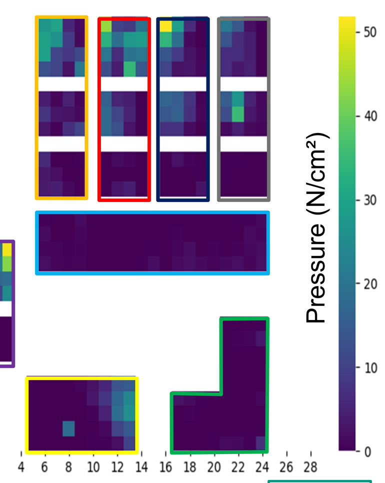

Fig. 10

Discussion & Conclusions

- Shaking movements showed **consistent movement patterns within individuals**, with variability occurring mainly in movement amplitude rather than frequency.
- A trend was observed between **sporting activity** and increased shaking frequency; however, this finding should be interpreted cautiously and verified in a larger cohort.
- Unlike previous studies that prescribed a fixed grip and constrained the shaking motion while focusing primarily on infant head trajectories and head accelerations using ATDs with limited biofidelity for the AHT-specific use case, this **study investigated the biomechanical load case** input by analyzing the upper-body kinematics of **participants from the typical offender age group**. Allowing participants to choose their natural grip and movement pattern provided a more realistic representation of unconstrained shaking behavior.
- The **multimodal measurement approach** combining Vicon-, ArUco-based tracking, and participant observation **enhanced the credibility** of the collected data. Participant observation captured grip adjustments, sensor slippage, and shaking behavior, while the complementary tracking systems enabled cross-validation of trajectories and kinematics.
- Although the grip force measurements require further methodological validation due to glove slippage and the limited haptic fidelity of the rigid ATD thorax, they represent a promising approach for investigating accompanying thoracic loading and potential injury mechanisms beyond head and neck kinematics.

References:

[1] Keenan, H.T. et al.: A population-based study of inflicted traumatic brain injury in young children. JAMA 290, 621–626 (2003). https://doi.org/10.1001/jama.290.5.621
[2] van Zandwijk, J.P., Vester, M.E.M., Bilo, R.A.C. et al.: Modeling of inflicted head injury by shaking trauma in children: what can we learn? Forensic Science, Medicine and Pathology 15, 423–436 (2019). https://doi.org/10.1007/s12024-019-00093-7
[3] Düser, T. et al.: Evaluation of the requirement delta between existing abusive head trauma (AHT) dummy concepts and the needs of forensic medicine and biomechanics research: Approaching multidisciplinary challenges in modeling AHT in the context of limited valid data. In: Colyer, C., Forster, J., Dell'Oro, M., Pope, K., Langman, L. (eds.) World Congress on Medical Physics and Biomedical Engineering 2025. IFMBE Proceedings. Springer International Publishing (2026).
[4] Lintern, T.O.: Modelling infant head kinematics in abusive head trauma. Doctoral dissertation, University of Auckland (2014).

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Presentation Number: P3-131