

Supplementary Material

Single-camera pose estimation for quantitative assessment of balance deficits: a proof-of-concept using graded acute alcohol intoxication

Domnik N., Lopez N., Unger T., Diekmann S., Tarnutzer A.A., Lamberg O.

This file contains supplementary methods, tables (Tables S1–S6) and figures (Figures S1–S2).

S1 Pose preprocessing

Body pose was estimated with Sapiens-1B applied frame by frame to each trial video, as described in the main text. The steps below repair frame geometry, convert the raw keypoint coordinates to body-relative units, and reject segments of insufficient quality, yielding for each keypoint a cleaned trajectory over the task window. All fixed threshold values are listed in Table S1.

S1.1 Participant isolation and tracking

Some recordings contained a second person (an assistant), so the participant had to be isolated from the multi-person detections. The participant was selected and tracked automatically by position in the frame. For the minority of trials in which an assistant stood near the frame center, the correct side was set manually, and frames with implausible tracking jumps (for example, an assistant walking in) were discarded. In one trial, a fall-and-catch split the participant across two Sapiens instances, which were reconstructed per keypoint and corrected manually.

S1.2 Geometry repair

Because the camera was framed for visual scoring rather than for pose estimation, a participant's ankles sometimes left the bottom of the frame. The missing ankle was reconstructed from the knee and a shank vector, scaled by the participant's own shank length measured from clean standing frames, or by standard anthropometric proportions [1] when too few clean frames were available. Camera motion (several trials were recorded handheld) was then compensated frame by frame with Oriented FAST and Rotated BRIEF (ORB) background features [2], registering each frame to a stable background.

S1.3 Conversion to body-relative units

Keypoint coordinates were then converted to body-relative units. A pixels-per-centimeter scale was estimated from known body-segment proportions [1], the hip center, taken as the midpoint between the left and right hip keypoints, was used as the origin, and all coordinates were divided by body height. Expressing positions as a fraction of body height makes the kinematics invariant to camera distance and image resolution, so trials recorded at different scales or orientations are directly comparable.

S1.4 Trajectory cleaning

Each keypoint trajectory was then cleaned. Low-confidence points were removed with a locally adaptive confidence threshold, physically implausible position jumps were discarded as outliers,

short gaps were linearly interpolated (longer gaps left missing), and the trajectories were low-pass filtered with a 6 Hz Butterworth filter to suppress jitter. An in-view check retained frames in which the participant was only partially detected, rather than discarding them outright. Keypoints that remained too sparse or discontinuous over a trial, judged by confidence coverage, interpolation-free continuity, and longest gap, were dropped for that trial.

S1.5 Task window and stance-leg normalization

Finally, each trial was reduced to the balance task itself by a task-window detection that excluded the walk-in, set-up, and waiting periods. For OLS trials, the stance leg was identified from the ankle heights and, where the left leg was the stance leg, the pose was mirrored about the vertical midline (with left and right labels swapped) so that the stance leg is always the right leg, enabling consistent cross-subject comparison. Tandem and TLS were left unmirrored.

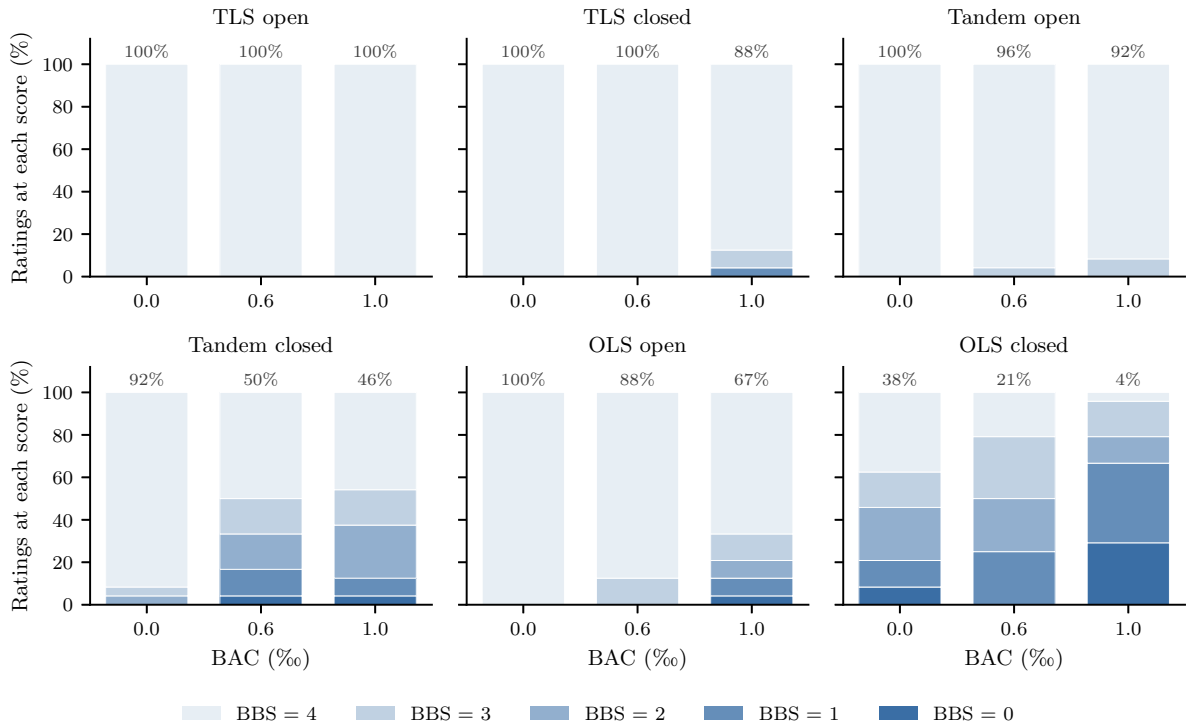


Figure S1. Distribution of BBS ratings by task and dose. Percentage of ratings at each score from 0 to 4, per task and BAC level, with the percentage at the maximum score of 4 above each bar. Each bar covers the 24 participants rated in that task at that dose. In eyes-open TLS every rating is a 4 at every dose, so the scale has no range in which to respond; the proportion below ceiling grows with task difficulty and with dose, and only in eyes-closed OLS is the full range of the scale used. *Abbreviations:* BAC, blood alcohol concentration; BBS, Berg Balance Scale; OLS, one-legged stance; TLS, two-legged stance.

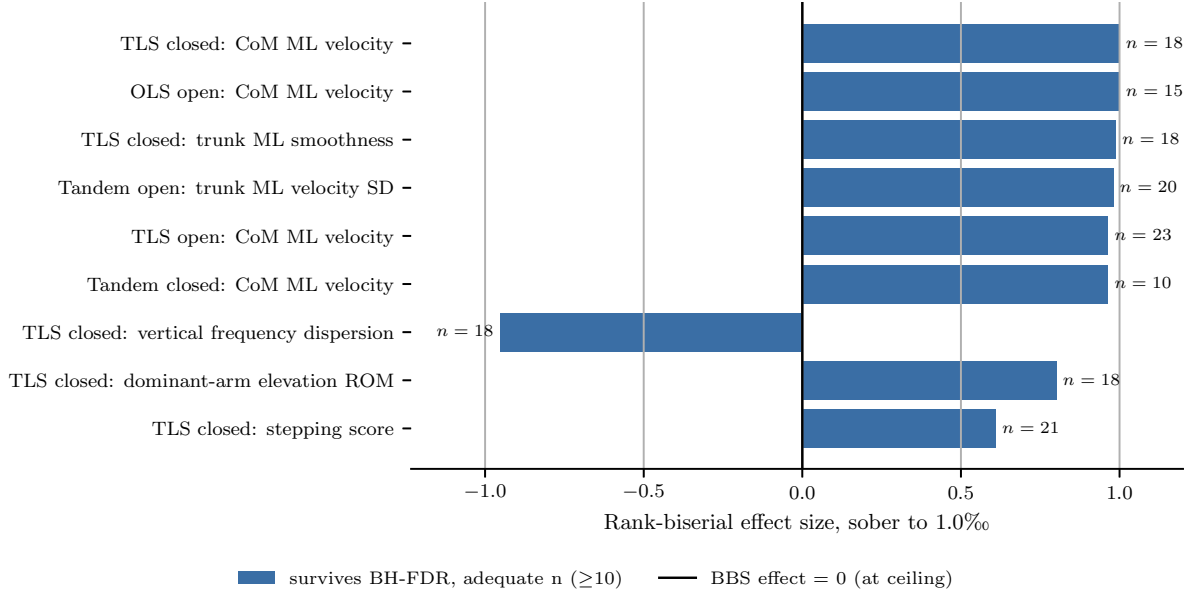


Figure S2. Digital metric response in the participants whose BBS rating was at ceiling. For each task-metric pair, the rank-biserial effect size of the sober to 1.0 ‰ change, restricted to participants awarded the maximum score of 4 at both doses. In this subset the BBS effect is exactly zero by construction, marked by the vertical line. The sign indicates only the direction of the metric with dose, negative for frequency dispersion, which decreases as instability rises; rows are ordered by magnitude. Annotations give the number of participants contributing to each comparison. *Abbreviations:* BBS, Berg Balance Scale; CoM, center of mass; FDR, false discovery rate; ML, mediolateral; OLS, one-legged stance; ROM, range of motion; TLS, two-legged stance.

Table S1. Fixed parameters of the pose-preprocessing pipeline. The pixel thresholds were tuned for the present footage ($\approx 1920 \times 1080$ at the laboratory’s fixed framing) and scale with image resolution and subject-to-camera distance. Frame-count thresholds assume 30 fps.

Stage	Parameter	Value
Participant selection	Min. body vertical extent	300 px
	Min. mean keypoint confidence	0.30
	Nose-jump rejection gate	40 px
De-merge	Per-keypoint matching gate	120 px
Confidence filter	Base threshold	0.70
	Floor threshold	0.50
	Adaptive threshold	20th percentile, ± 15 -frame window
Gap handling	Linear interpolation	gaps ≤ 5 frames
	Left missing	gaps > 5 frames
	Keypoint dropped (whole trial)	gap > 60 frames
Keypoint drop	Confidence coverage	< 0.70
	Clean coverage (continuity)	< 0.60
	Longest consecutive gap	> 60 frames

Table S2. The 167 digital metrics. Measures are grouped by construct, with axis and signal variants noted in the Measure column; all were computed within the task window from the normalized frontal-plane keypoints (X = mediolateral). An asterisk (*) marks exploratory measures, those without prior alcohol or markerless-pose precedent. The joint-angle “knee” measures are shank inclinations from vertical, not knee flexion. *Abbreviations:* CoM, center of mass; LTP, lower-trunk proxy; ML, mediolateral; SD, standard deviation; RMS, root-mean-square; SPARC, spectral arc length; PCA, principal component analysis; PSD, power spectral density; RQA, recurrence quantification analysis; %DET, %LAM, ENT, determinism, laminarity and entropy of the recurrence plot; SampEn, sample entropy; CRP, continuous relative phase; MARP, mean absolute relative phase; DP, deviation phase; EC/EO, eyes closed/eyes open; NHTSA, National Highway Traffic Safety Administration.

Family	Measure (variants)	Definition	Source
CoM	Mean and SD of resultant velocity	Mean and SD of the frame-to-frame resultant speed of the whole-body CoM.	[3]
CoM	Mean and SD of ML and vertical velocity	Mean and SD of CoM speed resolved separately onto the ML and vertical axes (alcohol-sensitive ML component).	[3, 4]
CoM	Acceleration and jerk (mean and SD)	Mean and SD of the first- and second-derivative magnitudes of CoM velocity (higher-order sway dynamics).	[3]
CoM	SPARC smoothness (ML)	Spectral arc length of the ML CoM speed profile; more negative = less smooth (noise-robust jerk surrogate).	[5]
CoM	Path length (total and per second)	Total distance traveled by the CoM, raw and normalized per second of valid recording.	[3, 6]
CoM	Displacement from mean (mean, max, SD)	Mean, maximum and SD of the radial distance of the CoM from its mean position.	[3]
CoM	RMS displacement (ML, vertical, resultant)	Root-mean-square excursion from the mean position, per axis and resultant.	[3]
CoM	95% prediction ellipse (area, orientation, eccentricity)	Area of the PCA/covariance-based 95% sway ellipse, plus its tilt angle and eccentricity (directional sway index).	[7]
CoM	Convex-hull sway area (total and per second)	Area of the convex hull enclosing the CoM trajectory, raw and per-second-normalized.	[3, 6]
CoM	Bounding-box sway area	Area of the axis-aligned bounding rectangle of the CoM trajectory.	[3]
CoM	Sway range (ML, vertical)	Peak-to-peak CoM excursion along the ML and vertical axes.	[3]
CoM	Spectral features (ML / vertical / combined)	Welch-PSD descriptors per axis: peak, power-weighted mean and median frequency, spectral dispersion, and total power.	[3]
CoM	Sample entropy (ML)*	SampEn ($m=2$, $r=0.2$ SD) of the ML CoM signal; regularity of sway (lower = more regular).	[8, 9]
CoM	RQA determinism and entropy*	Recurrence-quantification %DET (recurrence points on diagonal lines) and Shannon entropy of diagonal line lengths, at fixed 5% recurrence rate.	[10, 11]
CoM	RQA laminarity*	Recurrence-quantification %LAM (recurrence points on vertical lines) at fixed recurrence rate; sway intermittency.	[12, 11]
LTP	Mean resultant velocity	Mean frame-to-frame resultant speed of the lower-trunk proxy (shoulder–hip diagonal intersection).	[3]
LTP	Mean and SD of ML and vertical velocity	Mean and SD of lower-trunk-proxy speed resolved onto the ML and vertical axes.	[3, 4]
LTP	Acceleration and jerk (mean)	Mean first- and second-derivative magnitudes of lower-trunk-proxy velocity.	[3]
LTP	SPARC smoothness (ML)	Spectral arc length of the ML lower-trunk-proxy speed profile (noise-robust smoothness).	[5]
LTP	Path length (total and per second)	Total lower-trunk-proxy path traveled, raw and per-second-normalized.	[3, 6]

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Table S2 – continued

Family	Measure (variants)	Definition	Source
LTP	RMS displacement (ML, vertical, resultant)	Root-mean-square lower-trunk-proxy excursion from its mean position, per axis and resultant.	[3]
LTP	95% prediction ellipse (area, orientation, eccentricity)	Area, tilt angle and eccentricity of the 95% PCA sway ellipse of the lower-trunk proxy.	[7]
LTP	Convex-hull sway area (total and per second)	Convex-hull area of the lower-trunk-proxy trajectory, raw and per-second-normalized.	[3, 6]
LTP	Bounding-box sway area	Bounding-rectangle area of the lower-trunk-proxy trajectory.	[3]
LTP	Sample entropy (ML)*	SampEn of the ML lower-trunk-proxy signal; sway regularity.	[8, 9]
LTP	RQA determinism and entropy*	%DET and diagonal-line entropy of the recurrence plot of the ML lower-trunk-proxy signal.	[10, 11]
LTP	RQA laminarity*	%LAM of the recurrence plot of the ML lower-trunk-proxy signal.	[12, 11]
Angles	Segment range of motion	Range of motion (max–min) of each 2D segment-inclination angle: shoulder, pelvis and ear lines, trunk-from-vertical, and left/right shank inclination.	[1, 13]
Angles	Segment angular SD	SD (variability) of each segment-inclination angle across the trial.	[1, 13]
Angles	Segment RMS angular velocity	Root-mean-square of the time-derivative of each segment-inclination angle.	[1, 13]
Angles	Inter-segment MARP (shoulder–pelvis, pelvis–leg)*	Mean absolute ML continuous relative phase between the segment pairs; 0° in-phase to 180° anti-phase.	[14, 15]
Angles	Inter-segment DP (shoulder–pelvis, pelvis–leg)*	SD of the ML relative phase for each segment pair; coordination variability/stability.	[14, 15]
Stepping	Per-ankle displacement (mean, max, SD)	Mean, max and SD of each ankle’s radial displacement from its first in-window position.	[16]
Stepping	Steps above threshold	Per-ankle count of frames whose displacement exceeds the step threshold.	[16]
Stepping	Per-ankle velocity (mean, max, RMS)	Mean, max and RMS of each ankle’s frame-to-frame speed.	[16]
Stepping	Fast movements	Per-ankle count of frames exceeding the fast-movement (compensatory-step) velocity threshold.	[16]
Stepping	Displacement and step rate	Per-ankle mean displacement and step count normalized by trial duration.	[16, 6]
Stepping	Displacement asymmetry	Absolute left–right difference in mean ankle displacement (Standing tests only).	[16]
Stepping	Composite stepping score	Test-weighted combination of ankle displacement and RMS velocity (stance/support leg weighted by task). Weights were fixed a priori and were not tuned on these data.	[16]
Stepping	Binary stepped	1 if any test-relevant ankle exceeds the step threshold, 0 if stable, –1 if indeterminable.	[16]
Stepping	Discrete step events	Count of sustained ankle-speed bursts (merged across ankles), latency to first step, and mean inter-step interval.	[16, 17]
Stepping	Mediolateral step incidence	Count and fraction of discrete steps whose ML extent exceeds their vertical extent.	[16, 17]
Stepping	One-leg-stance duration	Single-leg-stance hold times from lifted-vs-stance ankle vertical separation: first-hold, longest, and total summed hold.	[18]
Stepping	One-leg-stance hold and touchdown counts	Number of sustained foot-up holds and number of recovered touch-downs.	[18, 19]

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Table S2 – continued

Family	Measure (variants)	Definition	Source
Stepping	One-leg-stance arm abduction	Max shoulder→wrist abduction angle from vertical and fraction of frames an arm exceeds the abduction threshold (NHTSA “uses arms” clue).	[19]
Stepping	Tandem stance width (mean, SD)	Mean and SD of the ML ankle separation during tandem stance (foot-placement covariate).	[20]
Romberg	CoM sway ratios (nine measures)	Eyes-closed vs. eyes-open contrast $(EC - EO)/(EC + EO) \times 100$ of each CoM sway measure (velocity, path, ellipse, hull, bounding box); visual-dependence index.	[21]
Romberg	LTP sway ratios (same nine measures)	Eyes-closed/eyes-open Romberg contrast of the corresponding lower-trunk-proxy sway measures.	[21]
Upper limb	Wrist excursion RMS (ML, vertical)*	Per-arm RMS wrist excursion (distal hand-sway) along the ML and vertical axes.	[16]
Upper limb	Wrist excursion dynamics*	Per-arm wrist path-per-second, mean speed, and convex-hull sway area.	[16]
Upper limb	Arm elevation (mean, max, range)*	Per-arm shoulder→wrist elevation angle from the downward trunk axis: mean, max and range.	[16]
Upper limb	Arm abduction fraction*	Per-arm fraction of frames the arm elevation exceeds the abduction threshold.	[16]
Upper limb	Arm elevation velocity*	Per-arm RMS of the time-derivative of the arm-elevation angle.	[16]
Upper limb	Wrist excursion asymmetry*	Absolute dominant–non-dominant difference in ML wrist RMS (compensation lopsidedness).	[16]

Table S3. Ordering accuracy as a function of the number of combined metrics. Within-subject dose-ordering accuracy of the digital score when the per-fold non-redundant set is capped at the k most responsive metrics. A dash indicates that the per-fold set never contained that many metrics, so the setting was not reachable. Both arms are evaluated at each k on the participants that both could score; the BBS item rating does not depend on k , so its accuracy varies only where that matched set does. This occurs in eyes-closed OLS alone, where the set falls from 22 participants at $k = 1$ to 15 at $k \geq 2$ and the rating reaches 0.73 rather than 0.71, so the $k = 1$ and $k \geq 2$ columns of that row are not directly comparable. *Abbreviations:* BBS, Berg Balance Scale; OLS, one-legged stance; TLS, two-legged stance.

Task	n	$k = 1$	$k = 2$	$k = 3$	$k = 4$	BBS
TLS open	23	0.90	0.90	–	–	0.50
TLS closed	21	0.79	0.92	0.90	0.90	0.55
Tandem open	22	0.86	0.86	–	–	0.53
Tandem closed	21	0.78	–	–	–	0.64
OLS open	20	0.93	–	–	–	0.60
OLS closed	22 / 15	0.70	0.78	0.78	–	0.71 / 0.73

S2 Baseline referencing of the digital metrics

Because each participant had a sober trial, we asked whether referencing the metrics to that personal baseline, by subtracting each participant’s sober values, would improve discrimination of the closely spaced 0.6-versus-1.0 ‰ pair. For a single metric it cannot: subtracting a per-participant constant shifts both of that participant’s remaining trials equally, so their within-subject ordering is unchanged, and the two representations gave identical accuracies wherever the same metric was selected (Table S4). Referencing can therefore act only by changing which metrics survive redundancy pruning, since the correlation structure differs between the two representations. It did change the selected set, and slightly for the worse: with three metrics

the ordering accuracy was 0.86 with absolute values against 0.82 with referencing. The absolute metrics were therefore retained.

Table S4. Absolute metrics versus per-subject baseline referencing. AUC for the 0.6-versus-1.0 % contrast when the digital score is built from the absolute metric values, and when each value is expressed relative to that participant’s sober trial. The sober condition is excluded from this contrast because subtracting it from itself is degenerate. *Within-subject* is the mean per-participant ordering of that participant’s own two trials; *pooled* is computed across all held-out trials.

Task	Within-subject AUC		Pooled AUC	
	Absolute	Referenced	Absolute	Referenced
TLS open	0.48	0.48	0.50	0.46
TLS closed	0.91	0.91	0.78	0.76
Tandem open	0.87	0.87	0.72	0.67
Tandem closed	0.52	0.44	0.51	0.49
OLS open	0.86	0.54	0.67	0.54
OLS closed	0.58	0.58	0.57	0.51
Mean	0.70	0.63	0.62	0.57

Table S5. Dose-pair components of the within-subject ordering accuracy. For each pair of dose levels, the fraction of matched-fold participants whose two trials the score placed in the correct order, ties counted as one-half, for the digital score and the concurrent BBS item rating. The mean of the three columns is the within-subject dose-ordering accuracy. *Abbreviations:* BBS, Berg Balance Scale; OLS, one-legged stance; TLS, two-legged stance.

Task	Digital score			BBS item rating		
	0 vs 0.6	0.6 vs 1.0	0 vs 1.0	0 vs 0.6	0.6 vs 1.0	0 vs 1.0
TLS open	0.83	0.96	0.91	0.50	0.50	0.50
TLS closed	0.81	0.90	1.00	0.50	0.57	0.57
Tandem open	0.73	0.93	0.91	0.52	0.52	0.55
Tandem closed	0.71	0.76	0.86	0.71	0.48	0.74
OLS open	0.80	1.00	1.00	0.58	0.60	0.63
OLS closed	0.73	0.73	0.87	0.63	0.77	0.80
Mean	0.77	0.88	0.92	0.57	0.57	0.63

Table S6. One-versus-rest AUC by dose level and task. Area under the receiver-operating characteristic curve for each dose level against the other two, for the digital score and the concurrent BBS item rating, on matched folds. The macro-AUC is the mean of the three per-level values. The intermediate 0.6‰ level is bounded near chance by construction, because the middle class of an ordered variable cannot be separated from the union of the outer classes by a monotone score. *Abbreviations:* AUC, area under the receiver-operating-characteristic curve; BBS, Berg Balance Scale; OLS, one-legged stance; TLS, two-legged stance.

Task	Digital score				BBS item rating			
	0.0 ‰	0.6 ‰	1.0 ‰	Macro	0.0 ‰	0.6 ‰	1.0 ‰	Macro
TLS open	0.87	0.54	0.93	0.78	0.50	0.50	0.50	0.50
TLS closed	0.90	0.67	0.95	0.84	0.54	0.54	0.57	0.55
Tandem open	0.82	0.56	0.92	0.77	0.53	0.50	0.53	0.52
Tandem closed	0.79	0.36	0.81	0.65	0.73	0.48	0.61	0.60
OLS open	0.90	0.55	1.00	0.82	0.60	0.51	0.61	0.58
OLS closed	0.80	0.60	0.80	0.73	0.72	0.73	0.78	0.74

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