Motionprint Ergo

NIOSH Lifting Equation Module

Validation of Body-Position Variable Extraction

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1. Executive Summary

This report presents the results of a laboratory validation study for the NIOSH Revised Lifting Equation (RLE) module of **Motionprint Ergo**, an ergonomic assessment application developed by Motionprint BV. Motionprint Ergo is designed to work on motion capture data to automate ergonomic assessments. In this study, the Xsens MVN Awinda inertial motion capture system was used as the input source to evaluate the accuracy with which Motionprint Ergo extracts the key body-position variables required by the NIOSH equation: horizontal distance (H), vertical height at origin and destination (V), and asymmetry angle (A).

Three subjects performed a total of 45 lifting trials across five station configurations covering a range of practical lifting scenarios, from near/far reach and floor-level to overhead, both symmetric and asymmetric. Motionprint Ergo's output was compared against physically measured reference positions for each trial.

Key finding: The overall mean absolute errors were 3.4 cm for H, 2.8 cm for V at origin, 3.6 cm for V at destination, and 3.4° for the asymmetry angle. These results are consistent with the known positional accuracy of the Xsens MVN system and confirm that Motionprint Ergo provides reliable body-position measurements suitable for practical NIOSH lifting assessments.

2. Introduction

The NIOSH Revised Lifting Equation (Waters et al., 1994) is the most widely used tool for evaluating the physical demands of manual lifting tasks. It calculates a Recommended Weight Limit (RWL) and Lifting Index (LI) based on task parameters including the position of the load relative to the worker's body. Traditionally, these position variables are measured manually using tape measures—a process that is time-consuming, subject to inter-rater variability, and impractical for high-throughput assessments.

Motionprint Ergo addresses this by automating the extraction of body-position variables from motion capture data. Rather than requiring an ergonomist to manually measure distances and angles for each lift, Motionprint Ergo processes body-landmark coordinate data to compute H, V, and A directly, then applies the standard NIOSH multiplier formulas to produce the RWL and LI.

For this validation study, the **Xsens MVN Awinda** inertial motion capture system was used as the motion data source. The purpose of the study is to validate the accuracy of Motionprint Ergo's body-position variable extraction under controlled laboratory conditions using this specific input source.

The study follows a **two-layer validation strategy**, recognizing that there are two distinct sources of potential error in the automated pipeline:

Layer 1 — Calculation accuracy. The NIOSH multiplier formulas and RWL/LI computations are deterministic arithmetic operations. Given correct input values, they always produce the correct output. These calculations were verified by hand-calculation against the published NIOSH formulas for a selection of representative trials, and confirmed exact agreement. This verification covers both the single-task NIOSH analysis (RWL and LI) and the multi-task Composite Lifting

Index (CLI) procedure (Waters et al., 2007), both of which are implemented in Motionprint Ergo. Since these are deterministic formulas, once verified, no further empirical testing of the calculation layer is necessary.

Layer 2 — Position variable extraction accuracy. This is the core focus of the present validation. The challenge lies in how accurately the motion capture body model's landmark positions translate into the NIOSH position variables. Any error in the final RWL/LI output is therefore attributable to the accuracy of the position inputs from the motion capture system, not to calculation errors in Motionprint Ergo's equation implementation. Since the single-task and multi-task NIOSH analyses rely on the same position variables (H, V, A), this validation of position extraction accuracy applies equally to both.

3. Background: The NIOSH Revised Lifting Equation

The NIOSH Revised Lifting Equation computes a Recommended Weight Limit (RWL) as the product of a load constant (LC = 23 kg) and six task-specific multipliers: RWL = LC × HM × VM × DM × AM × FM × CM. The Lifting Index (LI) is the ratio of the actual load weight to the RWL; an LI greater than 1.0 indicates that the task exceeds the recommended limit for most workers.

This validation focuses on the three body-position variables that Motionprint Ergo extracts from motion capture data:

Variable	Definition	Unit
H	Horizontal distance from the midpoint between the ankles to the midpoint between the hands	cm
V	Vertical height of the hand midpoint above the floor, measured at lift origin and destination	cm
A	Asymmetry angle between the horizontal projection of the load direction and the worker's stance direction	°

Table 1. NIOSH variables that Motionprint Ergo extracts from motion capture data.

The vertical travel distance D (|V_destination − V_origin|) is derived directly from the two V measurements and is therefore not validated as a separate variable. The remaining multipliers - Frequency Multiplier (FM) and Coupling Multiplier (CM) - are determined by user-input parameters (lift frequency, duration, and coupling quality) and do not depend on motion capture data.

4. Validation Approach

4.1 Two-Layer Strategy

As outlined in the introduction, the validation is structured around two layers. **Layer 1 (calculation correctness)** was verified analytically: for a selection of trials, the NIOSH multiplier values (HM, VM, DM, AM, FM, CM) and resulting RWL were hand-calculated from the raw position data using the published formulas and compared against Motionprint Ergo's output. In all cases the values matched exactly, confirming that the software correctly implements the NIOSH equations. This verification was performed for both the single-task RWL/LI calculations and the multi-task CLI procedure, which involves sorting tasks by decreasing Single-Task Lifting Index and computing incremental frequency adjustments as described by Waters et al. (2007). Since these are deterministic formulas, once verified, no further empirical testing of the calculation layer is necessary.

Layer 2 (position variable extraction) is the focus of this empirical validation. Lifting stations were set up with physically measured, known target positions for H, V, and A. Subjects performed standardized lifts at these stations while wearing the Xsens MVN Awinda system, and Motionprint Ergo extracted the position variables from the recorded motion data. The extracted values were then compared to the physical reference values to quantify measurement accuracy.

4.2 Measurement Methodology

Motionprint Ergo derives the NIOSH position variables from body-landmark coordinates provided by the motion capture body model. Specifically, H is computed as the horizontal distance between the midpoint of the ankle landmarks and the midpoint of the hand landmarks. V is taken as the vertical height of the hand midpoint above the floor, as reported by the motion capture system.

A is derived from the angle between the horizontal projection of the ankle-to-hand vector and the worker’s stance direction, defined as the average forward orientation of both foot segments. Using the foot-based reference rather than the pelvis ensures that torso twist relative to the feet is correctly captured as asymmetry, consistent with the NIOSH definition of the mid-sagittal plane.

These geometric operations follow the definitions in the NIOSH Applications Manual (Waters et al., 1994). It is important to note that these calculations are unambiguous: given exact body-landmark positions, the results are exact. Therefore, any deviation between Motionprint Ergo’s output and the physical reference is attributable to the accuracy of the motion capture body model’s landmark position estimates, not to Motionprint Ergo’s computational logic.

5. Method

5.1 Equipment

Motion capture data were recorded using the **Xsens MVN Awinda** wireless inertial measurement unit (IMU) system (Paulich et al., 2018). Subjects wore a full-body sensor configuration. Calibration was performed using the N-pose with walking procedure prior to each data collection session. All recordings were HD reprocessed in **MVN Analyze Pro 2025.0** (Schepers et al., 2018) before being exported to .mvnx files for import into Motionprint Ergo.

5.2 Body Model Configuration

For each subject, all individual body segment lengths were manually measured and entered into the Xsens MVN software to configure the body model. While MVN Analyze Pro offers the option to estimate body segment lengths from height and foot length alone (using its built-in anthropometric database), manually entering all segment dimensions is recommended for best results. This is particularly important for absolute position-based variables such as H and V, where the accuracy of the body model's segment proportions directly affects the computed landmark positions. By entering measured segment lengths for each subject, the body model is tailored to the individual, minimizing systematic offsets that could arise from population-average segment ratio estimates.

5.3 Test Setup

The validation was conducted using a purpose-built test setup consisting of two height-adjustable stations - one serving as the lift origin and the other as the destination. The station heights were configured to match each of the five target configurations. A steel tape measure (±1 mm accuracy) was used to verify all station heights and horizontal distances.

Foot placement positions were marked on the floor with tape to ensure consistent subject positioning across trials. For the asymmetric lifting condition (C5), the destination station was positioned at a 45° angle relative to the subject's forward-facing direction, with tape marks on the floor guiding the correct placement. The test load (10 kg) was verified using a calibrated scale (±0.1 kg).

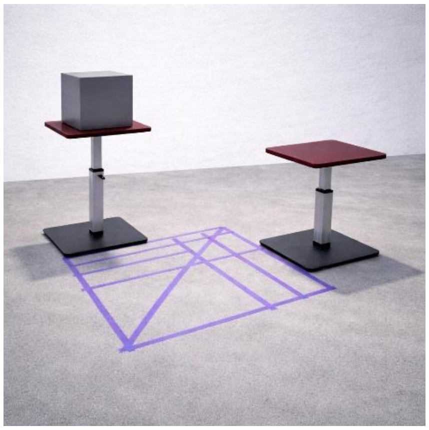

Figure 1. Validation test setup showing the origin station (left), destination station (right), and floor tape marks for foot placement and asymmetry angle. Stations were adjusted to the required height for each configuration.

5.4 Station Configurations

Five lifting station configurations were designed to cover a representative range of practical lifting scenarios:

Config	Description	Target H (cm)	Target V_origin (cm)	Target V_dest (cm)	Target A (°)
C1	Near / High (optimal zone)	40	77	101	0
C2	Far / Low	65	38	77	0
C3	Near / Floor level	40	22	77	0
C4	Far / High shelf (lowering)	65	122	53	0
C5	Asymmetric lift	50	77	122	45

Table 2. Station configurations. All configurations used a 10 kg load with good coupling, at a frequency of 1.0 lift/min (Short duration).

Configuration C4 represents a lowering task (destination is lower than origin), which is a valid NIOSH assessment scenario. Configurations C1 through C4 are symmetric lifts (target A = 0°), while C5 introduces an intentional 45° asymmetry.

5.5 Participants

Three healthy adult subjects (S01, S02, S03) participated in the study. All were free of musculoskeletal complaints at the time of data collection. Detailed demographic data were not recorded for this technical validation; the focus was on comparing measured versus reference positions across a range of body sizes rather than on establishing population norms.

5.6 Procedure

Each subject performed three trials per station configuration, yielding 15 trials per subject and 45 trials in total (5 configurations × 3 subjects × 3 trials). For each trial, the subject stood at the marked foot positions, grasped the 10 kg load at the origin station, and lifted (or lowered, in the case of C4) the load to the destination station. The Xsens MVN Awinda system recorded full-body kinematics throughout each trial.

After recording, all trials were HD reprocessed in MVN Analyze Pro 2025.0 and exported as .mvnx files. These files were imported into Motionprint Ergo, where the analyst identified the origin and destination frames within each recording. Motionprint Ergo extracted the body-position variables (H, V at origin, V at destination, and A) for the selected frames. The extracted values were then compared against the physically measured target values to compute measurement errors.

6. Results

6.1 Horizontal Distance (H)

Config	N	Mean Error (cm)	SD	MAE	RMSE	Min	Max
C1	9	+0.62	4.34	3.88	4.14	−5.35	+5.53
C2	9	−3.47	1.18	3.47	3.65	−5.50	−1.90
C3	9	−2.62	1.05	2.62	2.81	−4.40	−1.00
C4	9	−3.07	1.47	3.07	3.37	−5.45	−2.00
C5	9	−4.02	1.71	4.02	4.33	−7.10	−1.91
Overall	**45**	**−2.51**	**2.74**	**3.41**	**3.70**	**−7.10**	**+5.53**

Table 3. H measurement errors by configuration (App − Target).

Motionprint Ergo shows a mild negative bias in H (−2.51 cm on average), indicating a tendency to report hands slightly closer to the ankles than the physical reference. This is consistent with the Xsens hand landmark being located slightly proximal to the actual grip center. The overall MAE of 3.41 cm demonstrates good practical accuracy for this variable.

6.2 Vertical Height at Origin (V_origin)

Config	N	Mean Error (cm)	SD	MAE	RMSE	Min	Max
C1	9	−1.74	3.33	3.52	3.59	−4.44	+3.21
C2	9	−1.31	2.34	2.07	2.57	−4.61	+1.50
C3	9	+2.49	1.05	2.49	2.68	+1.14	+4.01
C4	9	−4.23	2.15	4.23	4.69	−7.55	−1.44
C5	9	+0.46	2.16	1.85	2.09	−3.33	+2.84
Overall	**45**	**−0.87**	**3.17**	**2.83**	**3.26**	**−7.55**	**+4.01**

Table 4. V_origin measurement errors by configuration.

V_origin shows minimal systematic bias overall (−0.87 cm). The largest errors occurred in C4 (high shelf position, V_origin = 122 cm), where the Xsens body model's hand position estimate appears to be slightly lower than the actual grip height. This is consistent with known Xsens position accuracy at extended reach heights.

6.3 Vertical Height at Destination (V_dest)

Config	N	Mean Error (cm)	SD	MAE	RMSE	Min	Max
C1	9	−1.73	1.80	1.83	2.42	−4.75	+0.48
C2	9	−2.08	4.15	4.20	4.43	−6.56	+3.92
C3	9	−2.02	3.66	3.81	4.00	−6.52	+3.11
C4	9	+1.63	5.14	3.94	5.12	−3.41	+8.87
C5	9	−4.18	1.90	4.18	4.54	−7.27	−2.53
Overall	**45**	**−1.67**	**3.90**	**3.59**	**4.20**	**−7.27**	**+8.87**

Table 5. V_dest measurement errors by configuration.

V_dest shows a small overall negative bias (−1.67 cm). The variability is somewhat higher than for V_origin, which is expected since destination positions often involve greater postural variability as subjects place the load.

6.4 Asymmetry Angle (A)

Condition	N	Mean Error (°)	SD	MAE	RMSE	Min	Max
C5 (target = 45°)	9	+2.84	2.34	3.39	3.60	−2.45	+6.21
C1–C4 (target = 0°)	36	+4.29	1.28	4.29	4.48	+1.67	+6.73

Table 6. Asymmetry angle errors. C5 is the intentional asymmetry condition; C1–C4 show spurious asymmetry in symmetric lifts.

For the intentional asymmetry condition (C5, target 45°), the MAE of 3.39° confirms good measurement accuracy. An observation of practical interest is the consistent reporting of small asymmetry values (mean 4.29°) in nominally symmetric lifts (C1–C4, target A = 0°). This is a known characteristic of human lifting: even when instructed to lift symmetrically, individuals naturally exhibit small rotational asymmetries. The Xsens system detects these real sub-clinical asymmetries. From a practical standpoint, asymmetry values in this range have negligible impact on the Asymmetric Multiplier (at A = 5°, AM = 1 − 0.0032 × 5 = 0.984, effectively 1.0).

6.5 Per-Subject Breakdown

Subject	H Mean Err.	H MAE	V_orig Mean Err.	V_orig MAE	V_dest Mean Err.	V_dest MAE
S01	−3.92	3.92	+0.13	2.52	+2.06	3.59
S02	−1.28	3.06	−1.10	2.54	−3.53	3.53
S03	−2.35	3.26	−1.64	3.45	−3.55	3.65

Table 7. Per-subject error summary (all configurations pooled).

Error magnitudes are broadly consistent across subjects, indicating that the accuracy is not driven by a single outlier. Minor inter-subject differences are expected due to variations in body dimensions, calibration quality, and natural movement patterns.

6.6 Bias Summary

Variable	Mean Bias	Interpretation
H	−2.51 cm	Hands reported slightly closer to ankles; consistent with Xsens hand landmark being proximal to grip center
V_origin	−0.87 cm	Minimal systematic bias
V_dest	−1.67 cm	Small negative bias; hands read slightly lower than reference at destination

Table 8. Summary of systematic biases.

7. Discussion

7.1 Error Attribution

The errors observed in this validation are **not caused by Motionprint Ergo's calculation logic**. The application performs straightforward geometric operations on body-landmark coordinates provided by the motion capture system. Given exact landmark positions, the computed H, V, and A values would be exact. The observed deviations from the physical reference are attributable to several characteristics of the IMU-based motion capture approach:

Motion capture body model estimation errors. The Xsens system estimates joint and segment positions from inertial sensor data. These estimates carry known uncertainty, typically in the range of 1–3 cm per joint position, as documented in the Xsens MVN technical specifications (Schepers et al., 2018; Paulich et al., 2018).

Calibration quality. The initial N-pose calibration establishes the body model dimensions for each subject. Although individual segment lengths were entered manually for optimal accuracy, small residual errors in the calibration posture can introduce systematic offsets that persist throughout the recording session.

Soft-tissue artifact. Sensors attached to the body surface shift slightly during movement due to underlying soft tissue motion, contributing to positional noise.

Natural movement variability. Subjects do not achieve identical hand and body positions on every repetition. Even with marked target positions, the actual hand location at the moment of grasp or placement varies by several centimeters between trials.

The key observation is that Motionprint Ergo is a *consumer* of motion capture data, not the *source* of its measurement uncertainty. If the Xsens body model places the hand position 3 cm from its true location, Motionprint Ergo's H and V values will reflect that offset—this is expected and correct behavior. The observed error magnitudes (~3–5 cm for position variables, ~3–5° for asymmetry) are **consistent with the known accuracy of the Xsens MVN system** for positional data, confirming that Motionprint Ergo does not introduce additional error beyond what the motion capture system provides.

7.2 Practical Implications for Ergonomists

For ergonomists considering Motionprint Ergo for field use, the practical question is: how much does a measurement error of this magnitude affect the final NIOSH assessment? The impact depends on where in the variable's range the error occurs.

For the Vertical Multiplier ($VM = 1 - 0.003 \cdot |V - 75|$), a 3 cm error near the optimal height ($V \approx 75$ cm) changes VM by only 0.009 (from 1.000 to 0.991) - a negligible effect. For the Horizontal Multiplier ($HM = 25/H$), a 3 cm error at H = 40 cm changes HM from 0.625 to 0.581 (7% change). At H = 25 cm (minimum), the same error changes HM from 1.000 to 0.893 (11% change) - more impactful, but H values near the minimum are uncommon in practice.

It is also worth noting that traditional tape-measure methods are themselves subject to inter-rater variability, typically in the range of 2–3 cm for H and V measurements. The accuracy of Motionprint Ergo's automated extraction is therefore comparable to the precision achievable through careful manual measurement, with the significant advantages of speed and repeatability.

Beyond matching the accuracy of manual methods, Motionprint Ergo offers a fundamental advantage in the richness of the assessment. Because the motion capture system records the entire lifting movement continuously, Motionprint Ergo automatically measures and calculates all position variables throughout the whole recording—not only at the origin and destination poses. This means the NIOSH analysis is no longer limited to evaluating just two static postures. Within the NIOSH report settings in Motionprint Ergo, the user can choose to analyze the frame with the peak Lifting Index score rather than being restricted to the origin and destination frames. This capability captures the worst-case posture during the lift, which may occur at a point in the movement that a manual assessment would miss entirely.

7.3 Study Limitations

Sample size. Three subjects with three trials each provide 9 observations per configuration (45 total). This is sufficient for a technical validation and application note, but not for establishing population-level accuracy norms. Future studies with larger and more diverse samples would strengthen the evidence base.

Laboratory conditions. All trials were performed in a controlled laboratory environment with clearly marked positions. Real-world assessments involve more natural variability in posture, movement speed, and environmental constraints. Field accuracy may differ somewhat from these controlled results.

Single motion capture system. Results are specific to the Xsens MVN Awinda system used in this study. Motionprint Ergo is designed to work on motion capture data from various sources; performance with other systems will require separate validation.

Reference method. The ground truth in this study is the physically measured target station position, not a simultaneous tape-measure reading by an expert ergonomist at the exact hand position. In practice, the subject's actual hand position may deviate slightly from the target, which means some portion of the observed error is due to the subject's positioning rather than the measurement system.

Participant demographics. Detailed demographic information (age, height, weight) was not recorded in the dataset. While this does not affect the position-variable comparison, it limits the ability to assess whether body dimensions systematically influence accuracy.

8. Conclusion

This validation study demonstrates that Motionprint Ergo accurately extracts the body-position variables required for NIOSH Revised Lifting Equation assessments from Xsens MVN Awinda inertial motion capture data. Across 45 lifting trials spanning five representative station configurations, all position variables - horizontal distance (H), vertical height at origin and destination (V), and asymmetry angle (A) - demonstrated accuracy levels consistent with the known capabilities of the Xsens MVN system and comparable to inter-rater variability in traditional manual measurement methods.

Motionprint Ergo's NIOSH equation implementation, including both the single-task RWL/LI and multi-task CLI calculations, was independently verified through hand-calculation and confirmed to be correct.

Taken together, these results confirm that Motionprint Ergo provides a reliable and practical tool for automated NIOSH lifting assessments, suitable for use by ergonomists in both laboratory and field settings.

9. References

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