onform

3D Golf Swing Pose Estimation Model

Model Card

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1. Model Summary

Purpose

The Onform 3D pose estimation model reconstructs a golfer's swing in three dimensions from a single 2D video recorded from **face-on** (camera perpendicular to the target line) or **down-the-line** (camera aligned with the target line). From the reconstructed skeleton, biomechanical metrics are derived that enable an in-depth analysis of the golfer's swing.

Key note: At present, several derived metrics are only available when the swing video is captured from the *face-on view*. Support for the down-the-line view will be introduced in an upcoming release.

Inputs

- RGB video of a single full golf swing captured at 120 FPS or higher either:
    - Face-on (FO): camera perpendicular to the target line.
    - Down-the-line (DTL): camera aligned with the target line.

Outputs

- A sequence of 3D joint locations (avatar/skeleton) over the duration of the swing
- Derived biomechanical metrics, such as:
    - Torso and pelvis rotations and bends in degrees.
    - Sway, slide, thrust of the torso and pelvis in inches/cm.
    - Swing tempo, as a ratio of time of upswing to downswing.
    - X-Factor as difference in rotation between a golfer's torso and pelvis.
- Outputs are currently viewable in the Onform iOS application. Support for Android coming soon.

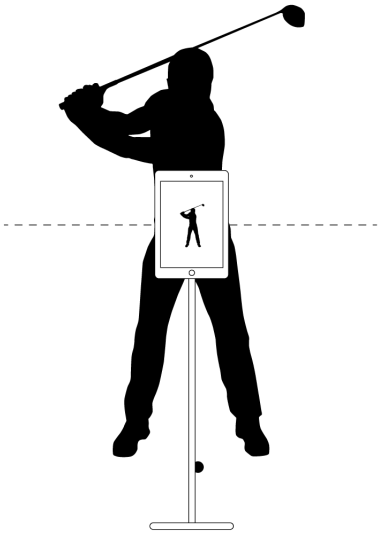
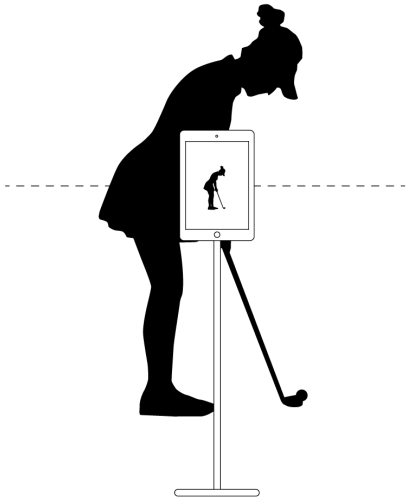
Training Data

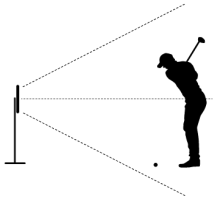
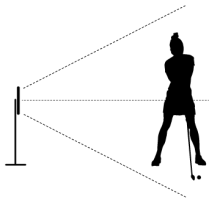
- Model built and tested on data collected from a scientific-grade 3D marker-based motion capture system (OptiTrack).
- Data includes 1200+ swings from 20+ athletes of various skill levels and body types.

2. Model Usage and Limitations

Video Capture Guidelines

Parameter	Recommendation
Camera Angle (Face-on)	Just as it does for 2D video, recording angles matter. We recommend pointing at the centre of the golfer, ideally perpendicular to the target line. Try to keep the camera as level as possible.
Camera Height	Place between waist to chest level of golfer
Distance from Golfer	Golfer's height is at least 50% of the video frame
Lighting	Well-lit, evenly distributed
Clothing	Avoid loose, baggy outfits that obscure joints
View Obstructions	Ensure the full body is visible throughout the swing. If possible, avoid background noise, such as other golfers.

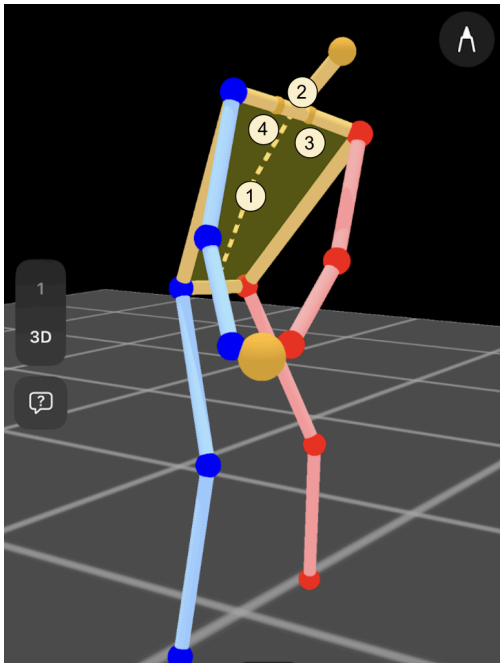
Face-On Camera Angle	**Down-The-Line** Camera Angle
	

Face-On Camera Angle (side view)	**Down-The-Line** Camera Angle (side view)
	

Limitations

- Full swings: While the model is very flexible, it is trained to work best with a full golf swing.
- Multicam setting: The face-on angle will be used for all metrics calculations and supplemented with thrust data from the down the line camera.
- Obstructions: If joints are obstructed or outside the video frame, accuracy may degrade.
- Environment: Model performs best in well-lit environments, with a single human in view.
- Clothing artifacts: Baggy or dark clothing may hinder pose estimation.

3. 3D Skeleton



The 3D skeleton consists of tracked joints representing the head, spine, upper limbs, and lower limbs.

- **Head & Spine:** Head, Neck, Mid Spine, Mid Pelvis, Left & Right of Rib Cage 1
- **Upper Body:** Left & Right Shoulders, Elbows, Wrists
- **Lower Body:** Left & Right Hips, Knees, Ankles

Torso Definition

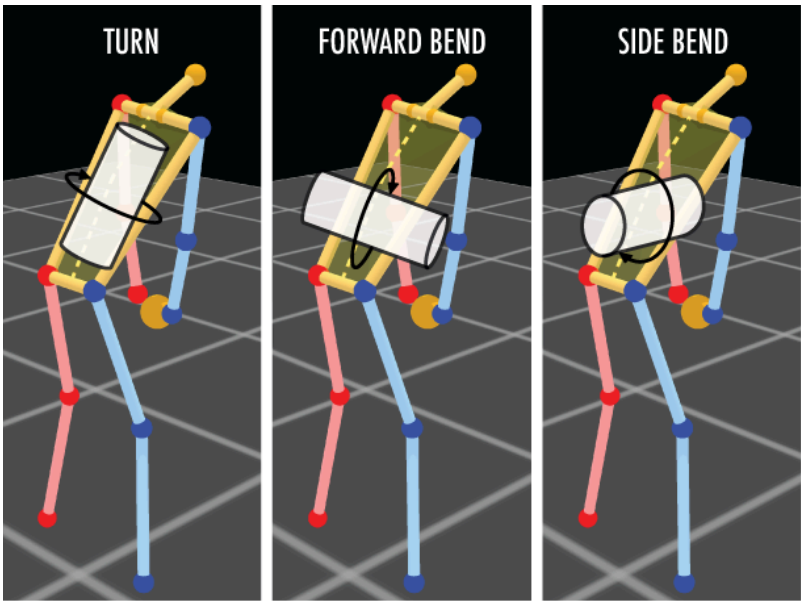
The torso segment is defined as the rigid body formed by the thorax bounded vertically by the **mid-spine joint (1)** and the **neck joint (2)**, and laterally by the centers of the **first rib cage on the left (3) and right (4) sides**. This four-point construction captures both the vertical alignment of the spine and the breadth of the upper thorax, providing an accurate basis for computing upper torso orientation and motion.

Because the lateral landmarks correspond to the **first rib level**, the orientation angles reported by the Onform system should be interpreted as ***upper-torso*** **orientation angles**.

It is important to note that different 3D golf biomechanics systems may define the torso segment using landmarks located at the **mid-thorax or lower thoracic region**. As such, measurements derived from different torso segment definitions are **not directly comparable**. In practice, upper-torso measurements typically exhibit **slightly greater axial rotation during the backswing and slightly less open rotation at impact** compared with measurements derived from mid-torso definitions.

4. 3D Body Metrics

Torso Orientation Angles



Upper torso orientation is computed using a **Cardan sequence** in the order **[rotation – side bend – forward bend]**.

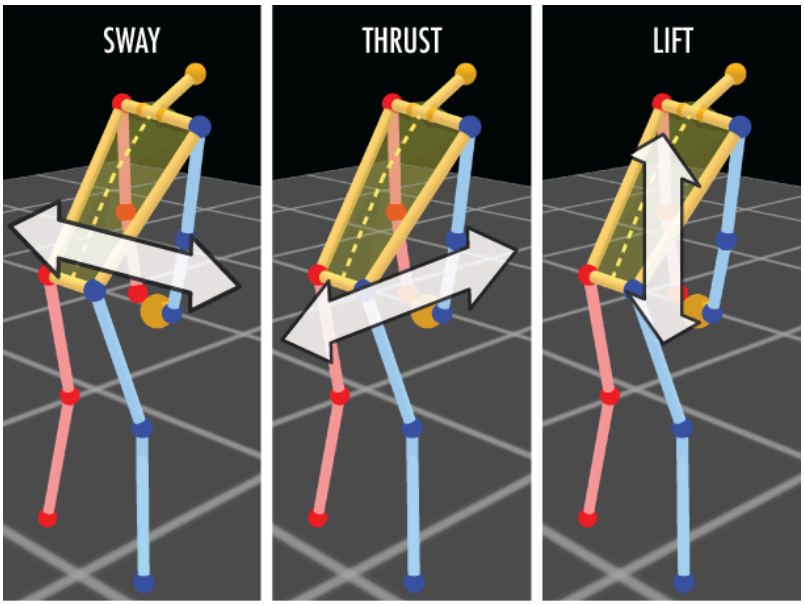
- **Turn:** Angle rotated about the spine axis of the torso, measured relative to the ankle line at address.
- **Forward bend:** Angle about the lateral (left-right) axis of the torso, measured relative to the global vertical reference axis.
- **Side bend:** Angle about the longitudinal (front-back) axis of the torso, measured relative to the global vertical reference axis.

Pelvis Turn

Pelvis turn is computed using the **spine-normal projection method**.

- The **lower spine axis** is defined by the line segment from the mid-pelvis to the mid-spine joint.
- Both the pelvis line (joining left and right hip joints) and the ankle line (joining left and right ankles) are projected onto the plane orthogonal to this axis.
- The angle between these two projected lines within the plane defines the **pelvis turn angle**.

Positional Displacements (sway, thrust, lift)



Displacement metrics are computed as changes in joint position relative to **address** (start of the swing):

- **Pelvis:** displacement of the **mid-pelvis joint**
- **Torso:** displacement of the **mid-spine joint**

Conventions:

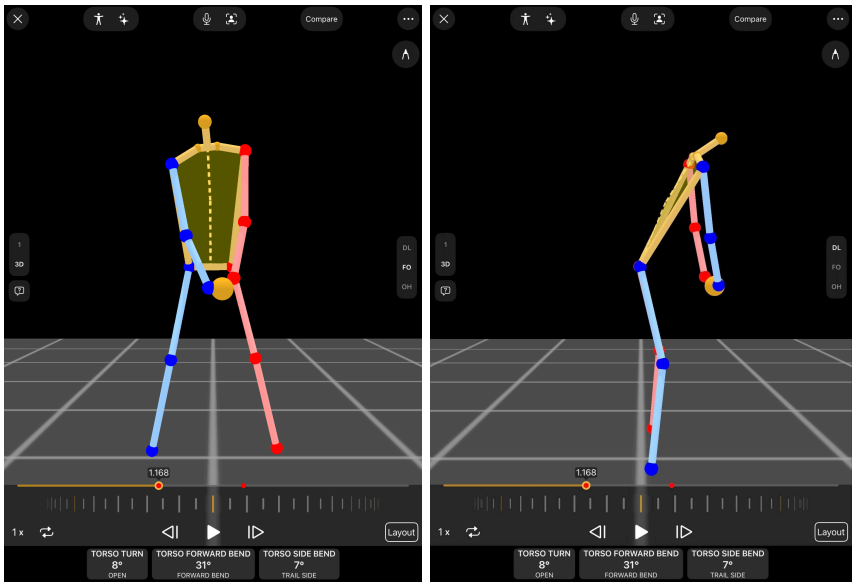
- **Sway:** towards and away from the target line
- **Thrust:** towards and away from the camera (face-on view)
- **Lift:** vertical displacement, up or down relative to the ground

X-Factor and Swing Tempo

- **X-Factor:** Difference in axial rotation between torso and pelvis, representing coil at the top of backswing.
- **Swing Tempo:** Ratio of backswing (upswing) duration to downswing duration.

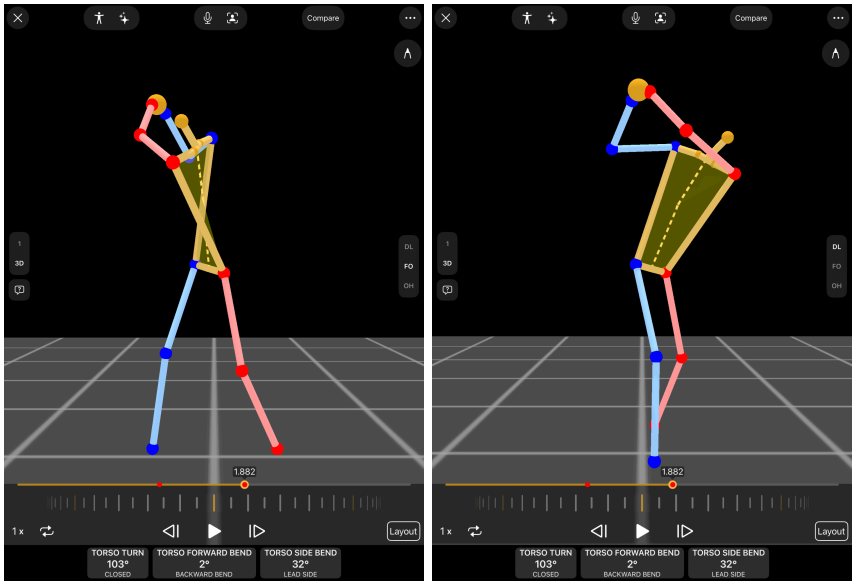
5. Swing Phases and Interpreting Torso Angles

Start of Swing (address):



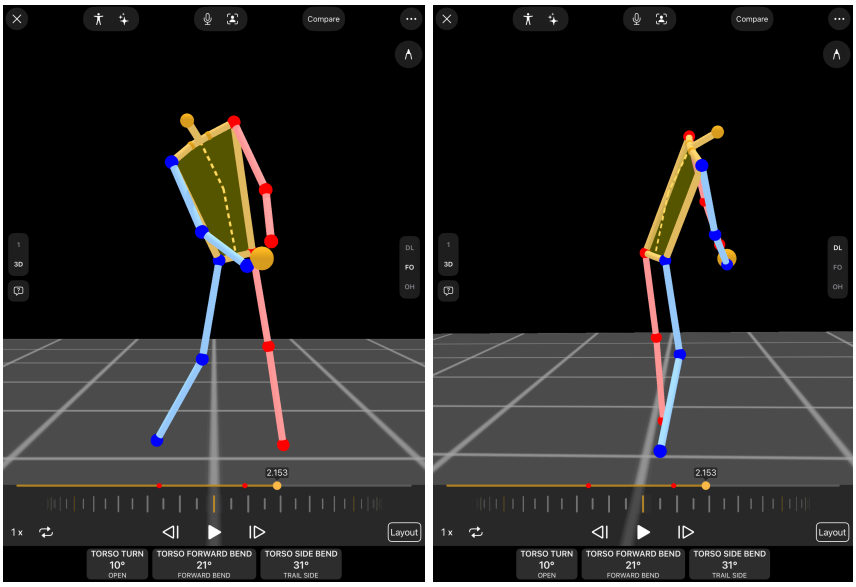
- Defined by the initial coordinated movement of both wrist joints.
- Typical torso values: **forward bend ~30°**, minimal axial turn and side bend.

Top of Backswing:



- Defined as the frame where the **left shoulder–left wrist line** reverses its rotational direction (clockwise → counterclockwise for right-handed golfers).
- Typical torso values: **turn ~100°**, **lead side bend ~30°**, **forward bend ≈ 0°**.
- **Note:** From a down-the-line perspective, the spine appears tilted downward. This tilt results from the combination of axial turn and lead side bend (left shoulder lowered), not from forward flexion of the torso.

Impact Position:



- Typical torso values: all three angles are significant — forward bend, trail side bend (right shoulder lowered), and axial turn open to target.
- **Note:** From a down-the-line view, the shoulder line may appear square to the target similar to the address position. Biomechanically, however, this alignment is achieved through a combination of trail side bend and open torso turn.

6. 3D Model evaluation

We validated our 3D model extensively using our internal motion tracker system and externally against three different systems. Details can be found below.

Internal Validation Results

The Onform 3D model for face-on swings has been internally benchmarked against the OptiTrack 3D marker based system. The tests were carried out on a set of 190 swings from 3 athletes of different abilities.

Metric	MAE - Top of Backswing	MAE - Impact
Pelvis Turn (°)	3.4°	3.1°
Torso Turn (°)	4.6°	2.5°
Torso Forward Bend (°)	2.7°	1.2°
Torso Side Bend (°)	2.2°	4.1°
Pelvis Sway	0.5 cm	0.6 cm
Pelvis Lift	0.6 cm	0.7 cm
Pelvis Thrust (DTL)	1.0 cm	0.9 cm

Table: Mean Absolute Error (MAE) values for key metrics (torso turn, forward bend, side bend, pelvis turn, sway, thrust, lift). MAE is the mean of the absolute differences between model predictions and ground-truth measurements across the test set. *Note: thrust is derived from the down-the-line model.*

External Validation Results

Important note: When comparing Onform 3D to other systems, it is essential to verify that the **metric definitions and orientation conventions** are equivalent. For example, torso orientation angles depend on the order of the Cardan sequence; mismatched definitions can yield large discrepancies even when both systems are internally consistent.

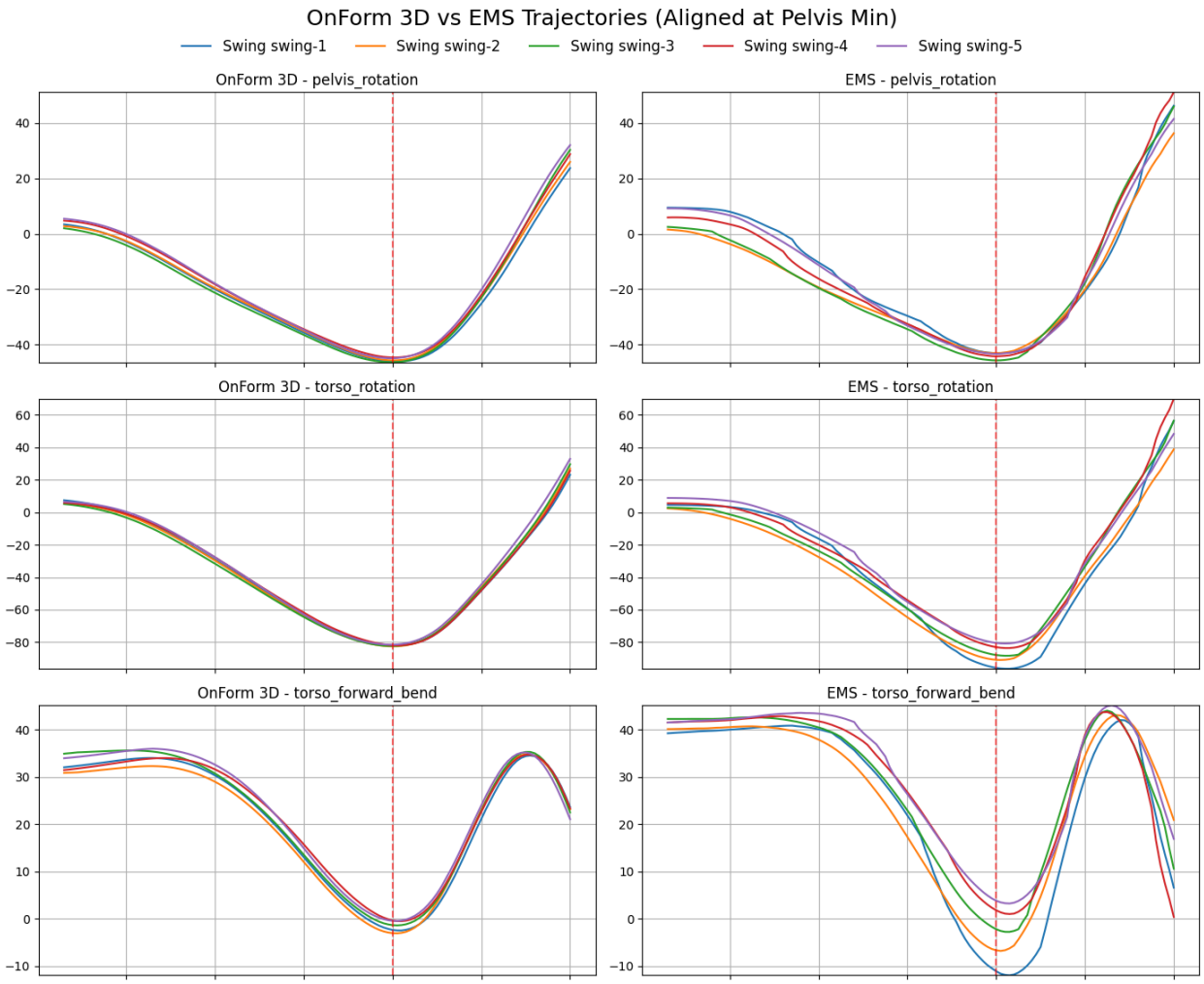
The Onform 3D model for face-on swings has been benchmarked against a well-regarded **electromagnetic tracking system (Polhemus based),** as well as two external **marker-based motion capture systems (Qualisys and Gears, which uses OptiTrack)**. The tests were carried out on a set of 36 swings from 4 athletes.

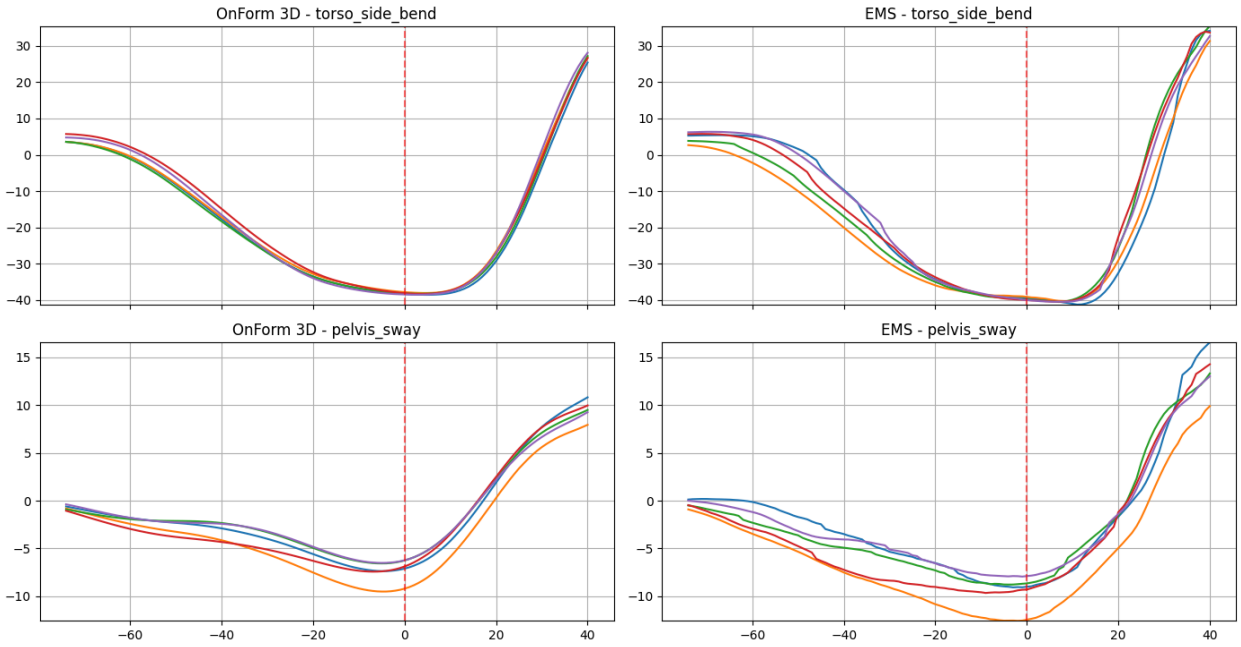
Metric	MAE - Top of Backswing	MAE - Impact
Pelvis Turn (°)	4.9°	4.1°
Torso Turn (°)	4.1°	6.4°

Metric	MAE - Top of Backswing	MAE - Impact
Torso Forward Bend (°)	6.8°	5.4°
Torso Side Bend (°)	2.8°	3.9°
Pelvis Sway	1.4 cm	1.8 cm
Pelvis Lift	0.7 cm	0.8 cm
Pelvis Thrust (DTL)	1.2 cm	1.0 cm

Validating Trajectories

The figure below compares five consistent swings of a pro player against the above mentioned EMS system (Polhemus based).





Key Observations:

- Electromagnetic traces are noisier due to sensor characteristics.
- Onform 3D outputs exhibit smooth, consistent trajectories.
- The model reproduces not only the values at key positions such as the top of backswing and impact, but also the full trajectory shape throughout the swing.

7. Kinematic sequence

Overview

The **kinematic sequence (KS)** describes the order and timing in which different body segments accelerate during the golf swing. It is visualized by plotting the **angular velocities of key body segments** throughout the swing.

In an efficient golf swing, rotational energy is generated by the body and transferred sequentially through the kinetic chain—from the lower body to the club. This results in a characteristic pattern where the **pelvis accelerates first, followed by the torso, arms, and finally the club**.

Analysing the kinematic sequence provides valuable insight into how a golfer generates power and how effectively that power is transferred through the body. Deviations from the typical sequence pattern may indicate issues such as inefficient timing between segments, poor energy transfer, or compensatory movement patterns.

Segments Included in the Kinematic Sequence

The Onform system computes the kinematic sequence using four rotating segments of the golfer's body and club. Angular velocity is computed as the first temporal derivative of the rotation angle, providing the instantaneous rotational speed of the segment throughout the swing.

Pelvis

The pelvis rotation corresponds to the **pelvis turn angle** defined earlier in this document.

Torso

The torso rotation corresponds to the **torso turn angle** defined earlier.

Lead Arm

The arm segment represents the **lead arm of the golfer** (left arm for a right-handed golfer). To compute the arm rotation:

- A line segment is defined between the **lead shoulder and lead wrist joints**.
- This segment is projected onto the plane perpendicular to the upper spine axis.
- The rotational angle of this projected segment is measured relative to a reference direction.

This approach captures the rotational motion of the lead arm as it accelerates through the downswing.

Club

The club segment represents the rotational motion of the golf club during the swing. Ideally, this motion would be computed using the 3D trajectory of the club head projected onto the swing plane. However, in the current implementation the club head trajectory is estimated from the 2D video, where the club segment is defined by line segment joining the club head and the wrist (approximating the grip end of the club) and the rotational angle is measured in the image plane.

Because this measurement does not account for the true 3D swing plane of the club, the resulting velocity curve represents an approximation of the club's rotational velocity and is displayed as a **dashed line** in the kinematic sequence chart.

Interpreting the Kinematic Sequence Chart

The kinematic sequence chart visualizes the angular velocities of the four segments throughout the swing. The **vertical axis** represents angular velocity measured in **degrees per second (°/s)**, while the **horizontal axis** represents the normalized swing time separated into the key swing phases.

Key swing positions are marked with vertical dotted lines:

- **P1 — Address**
- **P3 — Lead arm parallel in backswing**
- **P4 — Top of backswing**
- **P5 — Lead arm parallel in downswing**
- **P7 — Impact**
- **P8 — Follow-through**

For each segment, the **peak angular velocity** is identified and annotated on the chart. Peaks are defined as the **first local maximum occurring after the P4 position (top of backswing)**. This ensures that the detected peaks correspond to the downswing acceleration phase, where the sequential transfer of energy between body segments occurs.

The order in which these peaks occur represents the kinematic sequence of the swing. This detected sequence is displayed in the **top-right corner of the chart**, allowing coaches to quickly determine whether the golfer follows the typical sequencing pattern.

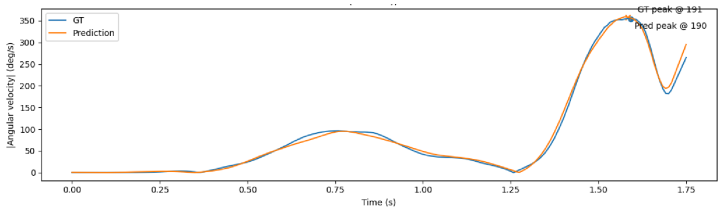
Kinematic Sequence Validation

The kinematic sequence estimated by the Onform system was validated against the angular velocity measurements obtained from the OptiTrack 3D marker based system.

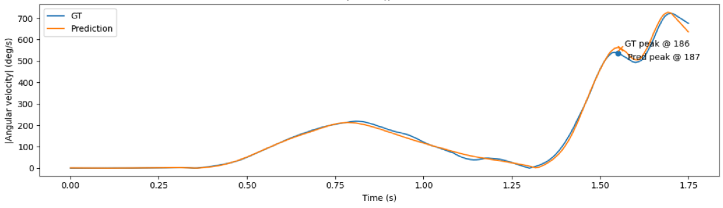
Reference the charts below where we show an example comparison of the angular velocity curves for a representative swing. Across the evaluation dataset, that contained 123 swings from 3 pro golfers, the **estimated sequence of peak velocities matched the OptiTrack peak sequence in 94.6% of the evaluated swings**, demonstrating that the Onform system can reliably recover the timing relationships between body segments that characterize the kinematic sequence.

Note: To ensure robust measurement of the sequence, swings were excluded from the analysis when the OptiTrack velocity peaks of any pair of body segments occurred within two frames of each other at 120 FPS (≈16.7 ms). In these cases, the peaks occur nearly simultaneously, making the sequence ordering ambiguous.

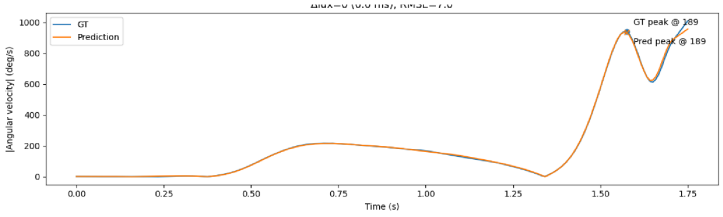
Pelvis



Torso



Lead Arm



8. Reference Ranges

To help coaches and golfers interpret the 3D biomechanical metrics produced by the Onform system, we compiled reference ranges based on the swings of elite professional golfers.

Dataset

The reference ranges were generated by analyzing the swings of the top 10 male and top 10 female golfers in the Official World Golf Ranking as of the publication of this model card, using the Onform 3D system. From these swings, we computed the statistical distributions of all available biomechanical metrics, including torso and pelvis rotations, bends, and positional displacements. These ranges represent typical motion patterns observed in elite golfers, providing a useful benchmark for evaluating a player's swing.

Gender and Club Specific Ranges

Because swing mechanics vary depending on **gender and club type**, the reference ranges are provided separately for **Male/Female golfers and Driver/Iron swings.** For each metric, the reference values are defined at three key swing positions: **Address, Top of Backswing and Impact.**

OnForm Reference Values (Mean)
Male & Female – Driver & Iron

Metric	Club	Address (M)	Address (F)	Top (M)	Top (F)	Impact (M)	Impact (F)
Torso Turn (°)	Driver	13.6	5.3	-105.9	-102.7	13.6	9.2
Torso Turn (°)	Iron	6.4	3.5	-96.7	-84.9	5.2	3.9
Torso Bend (°)	Driver	31.3	31.7	-4.7	-3.6	23.1	24.4
Torso Bend (°)	Iron	37.7	37.7	-0.7	7.4	34.9	35.8
Torso Side Bend (°)	Driver	10.9	5.2	-32.3	-30.5	33.0	28.4
Torso Side Bend (°)	Iron	8.1	4.8	-37.1	-35.0	26.2	20.4
Pelvis Turn (°)	Driver	6.6	1.3	-39.2	-39.7	40.1	32.6
Pelvis Turn (°)	Iron	3.5	0.9	-39.6	-35.1	32.1	27.9
Torso Sway (in)	Driver	0.0	0.0	0.8	-0.6	4.2	2.1
Torso Sway (in)	Iron	0.0	0.0	1.9	0.1	5.2	3.2
Pelvis Sway (in)	Driver	0.0	0.0	1.1	-0.1	6.3	3.9
Pelvis Sway (in)	Iron	0.0	0.0	2.0	0.6	6.2	3.9
Torso Lift (in)	Driver	0.0	0.0	0.8	0.4	-0.8	-1.4
Torso Lift (in)	Iron	0.0	0.0	0.7	0.3	-0.4	-0.7
Pelvis Lift (in)	Driver	0.0	0.0	1.0	0.7	-0.8	-1.3
Pelvis Lift (in)	Iron	0.0	0.0	1.0	0.7	-0.3	-0.5

Color-Coded Feedback

To make the metrics easier to interpret during swing analysis, Onform uses a **color-coding system** when displaying metric values. Each metric is compared against the professional reference distribution and categorized into one of three ranges:

Green (Typical Pro Range)
Values within **Mean ± 1 Standard Deviation** of the professional dataset.

Orange (Borderline Range)
Values within **Mean ± 2 Standard Deviations**, but outside the green range.

Red (Outside Pro Range)
Values that fall **outside ± 2 Standard Deviations** from the professional mean.

This colour coding allows coaches to quickly identify which aspects of a swing are **within typical professional ranges and which may differ significantly from elite patterns**.

Interpreting the Reference Ranges

The reference ranges are intended to provide **context rather than strict targets**. Golf swings can vary considerably between players due to differences in body structure, mobility, and swing style.

Therefore, these ranges should be used as a **guideline for comparison with elite golfers**, rather than as prescriptive values that every golfer must achieve.