

3D Non-Contact Whole Body Musculoskeletal Exercise Dataset

Aidan Kimberley | Ethan Matzek | Ava Megyeri



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Introductions





Aidan Kimberley

- McGill University
- B.Eng. in Mechanical Engineering
 - Altec Intern from 5/5 8/15
 - Data Analysis | Biomechanics







Ethan Matzek

- Wright State University
- M.S. in Computer Science and Engineering
 - Altec Intern from 5/12 8/8
- Computer Hardware & Software

- Ava Megyeri
- Wright State University
- Ph.D. in Computer Science and Engineering
 - Altec Intern from 5/27 8/15
 - Algorithm Development

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SECTION 1

Study Objectives

- •Capture a high-fidelity dataset across muscular-skeletal injury (MSKI) rehabilitation exercises to:
- 1. Design and validate custom 3D body tracking algorithms
- 2. Compare IR, RGB, and point-cloud data quality between different camera alternatives
- 3. Perform validation assessment of new solutions with respect to a reference motion capture system
- The Microsoft Kinect is discontinued and has become antiquated. Finding a suitable replacement for Kinect Body Tracking is the first step in moving away from depreciated hardware



MEDIC System

MUSCULOSKELETAL EVALUATION DEVICE FOR INJURY CONTROL SECTION 2





Purpose

- MSKIs are the leading cause of disabilities among warfighters
- •A majority of MSKIs are non-battle related, but rather stem from poor technique and excessive joint loading
- MEDIC was developed for exercise assessment, injury screening, developing injury resilience, and providing tailored biofeedback to users



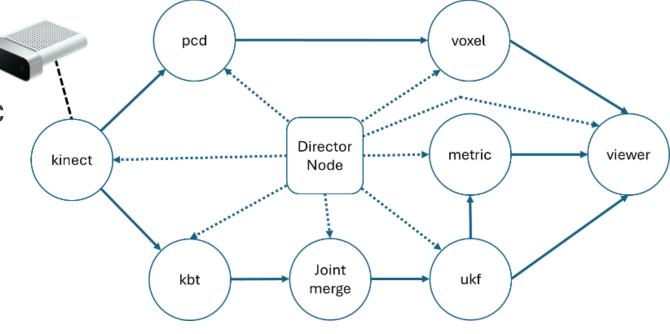
System Architecture

 MEDIC uses a node-based architecture

•Each node performs a specific function

A master node commands the other nodes

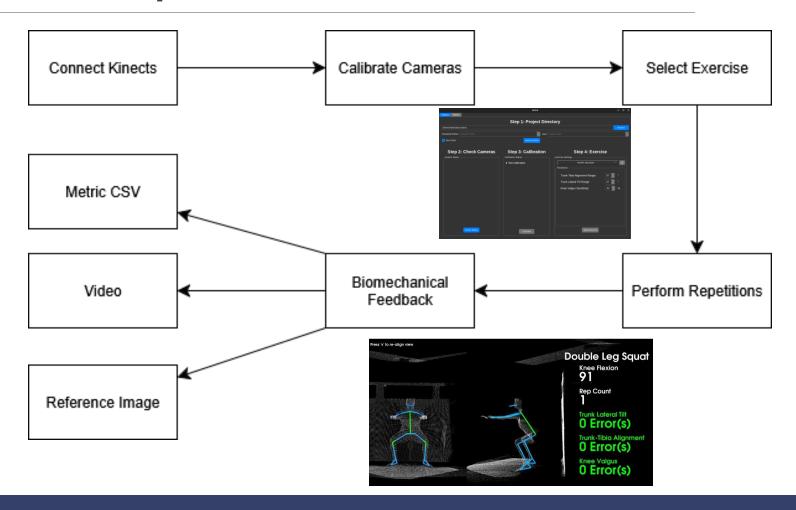
•Nodes communicate asynchronously, so they can run on separate PCs



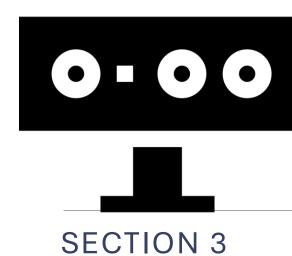


User Experience

- •MEDIC offers 9 common military battery exercises
 - 6 High exercises (3')
 - 3 Low exercises (1'6")
- •User interacts with the system through a GUI







16-Kinect System



Purpose

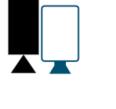
- •Evaluate current MEDIC biomechanical outcomes versus Vicon (reference standard)
- •Establish baseline feasibility of custom 3D human pose estimation algorithms
- •Set foundation for evaluating the trade-off between accuracy and number of cameras in pose estimation

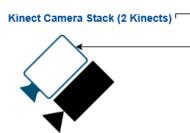


Hardware Requirements

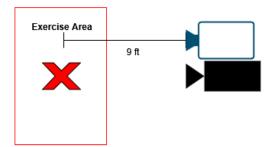
- •16 Kinects
 - RGB, Depth, and IR images
 - Native 30 FPS
- •Stacked cameras with time offset emulate 60 FPS capture
- Cameras positioned in a circle
 - 45° spacing
 - 9' radius
- •2 additional PCs required to run the system













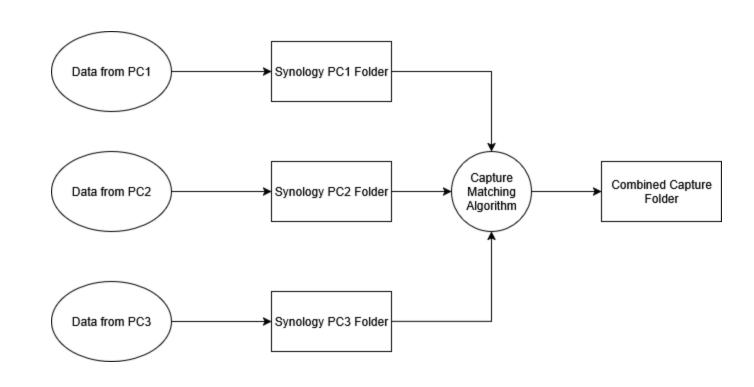




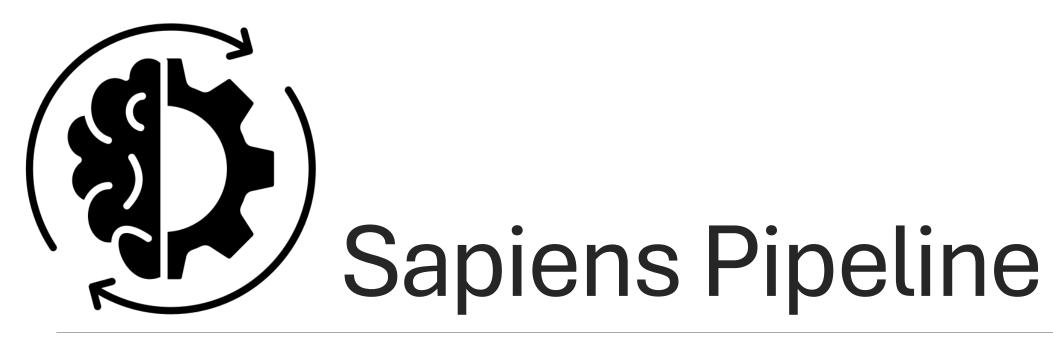


Software Requirements

- •Increasing output to 16 devices necessitates file management and bulk storage
- Each capture session records~1TB of data
- •A 10–gigabit ethernet switch connects the capture PCs to a central datacenter
- •Capture matching algorithms are used to transfer and combine data on the server







SECTION 4



Purpose

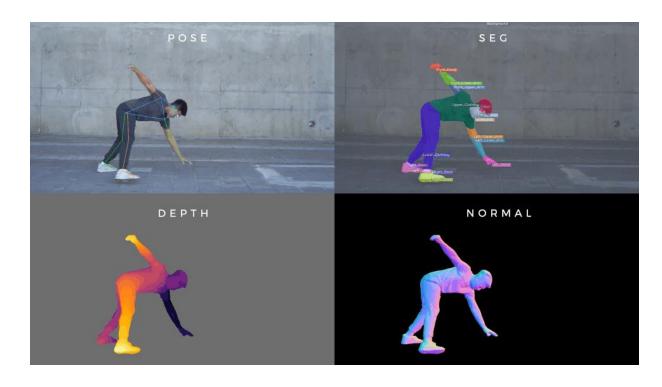
- Retain MEDIC functionality when retiring Kinect Body Tracking
- Create a model agnostic pipeline to find the best performing option

2D Pose Estimation Algorithm	Model Metadata
Real-Time Multi-Person 2D and 3D Whole-body Pose Estimation	Real-time, 133 keypoints
Real-Time Multi-Person Pose Estimation based on MMPose	Real-time, 17 or 26 keypoints
Sapiens 0.3 Billion	Real-time, 17 or 133 keypoints
Sapiens 0.6 Billion	Post, 17 or 133 keypoints
Sapiens 1 Billion	Post, 17 or 133 keypoints
Sapiens 2 Billion	Post, 17, or 133 keypoints
OpenPose	Real-time, 135 keypoints
MediaPipe	Real time, 33 keypoints



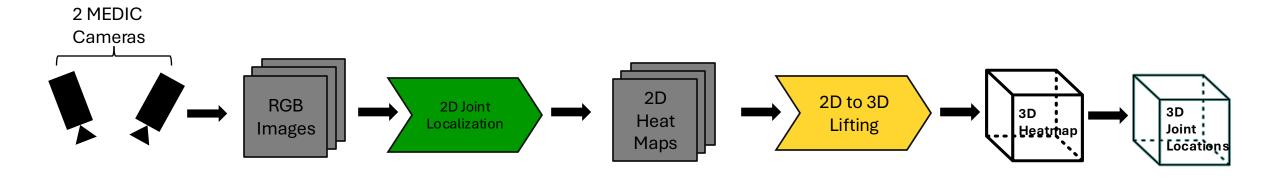
Sapiens Algorithm Overview

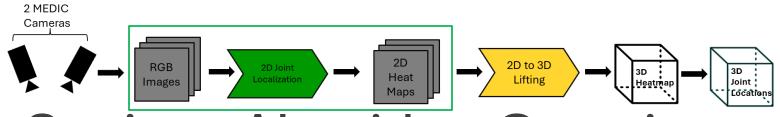
- •Sapiens is a foundation model for human-centric vision tasks
 - 2D pose estimation
 - Body-part segmentation
 - Depth estimation
 - Surface normal prediction



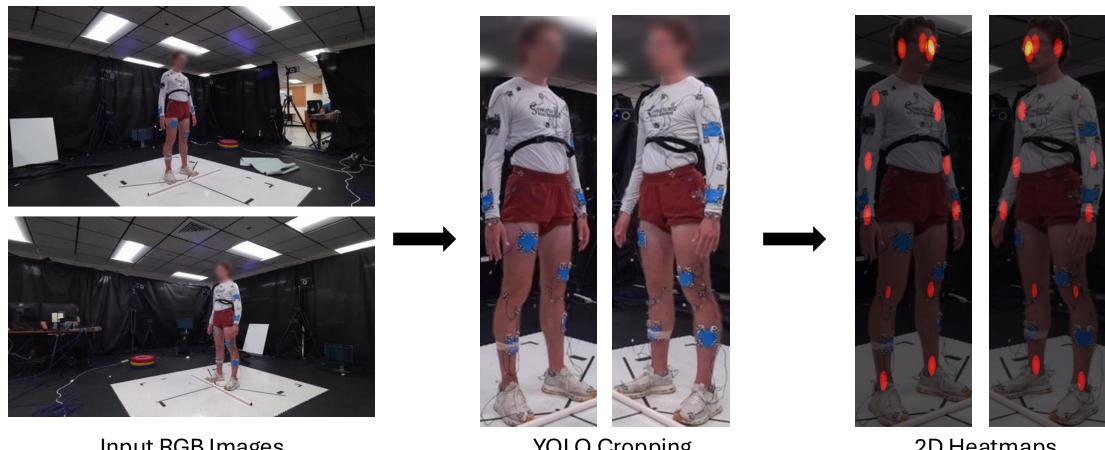


Overview of the Pipeline





Sapiens Algorithm Overview

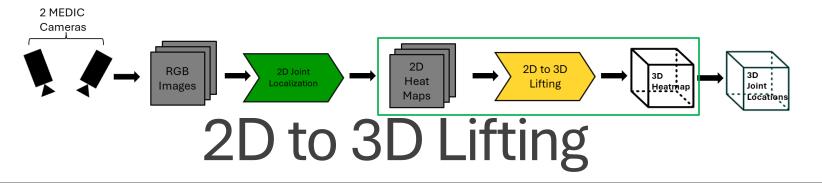


Input RGB Images

YOLO Cropping

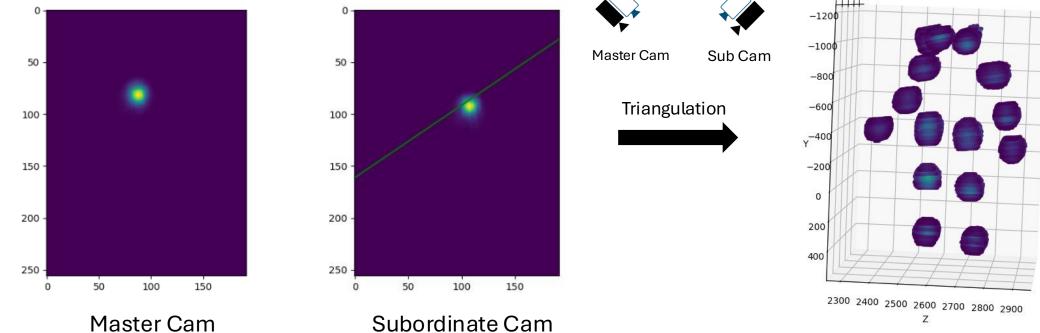
2D Heatmaps



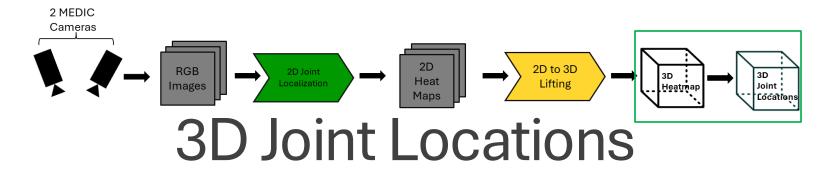


- 2 cameras viewpoints.
- •Create the fundamental matrix to relate the points from one viewpoint to another

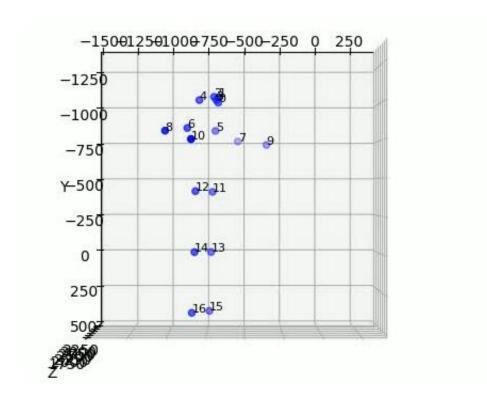
•Triangulate the points to get the 3D points

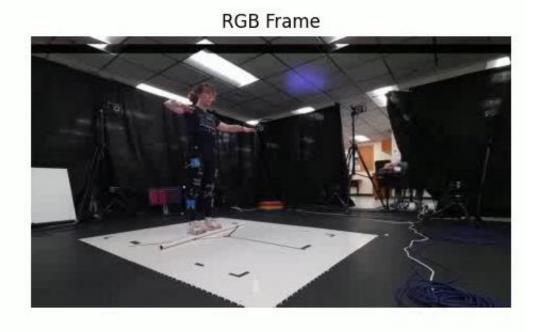






•Calculate the weighted mean of all points, using the probabilities as the weights





Feasibility Assessment

- Pipeline is model agnostic
 - All Sapiens model variations were confirmed to work
 - Open-source body tracking models use standardized inputs
 - Any off-the-shelf model can be used in the pipeline



Capabilities of the Pipeline

- Adding musculoskeletal constraints could improve the outputs
- •Different viewpoints can achieve more accurate 3D joints
- •Finetune the algorithm for our use-case to improve accuracy



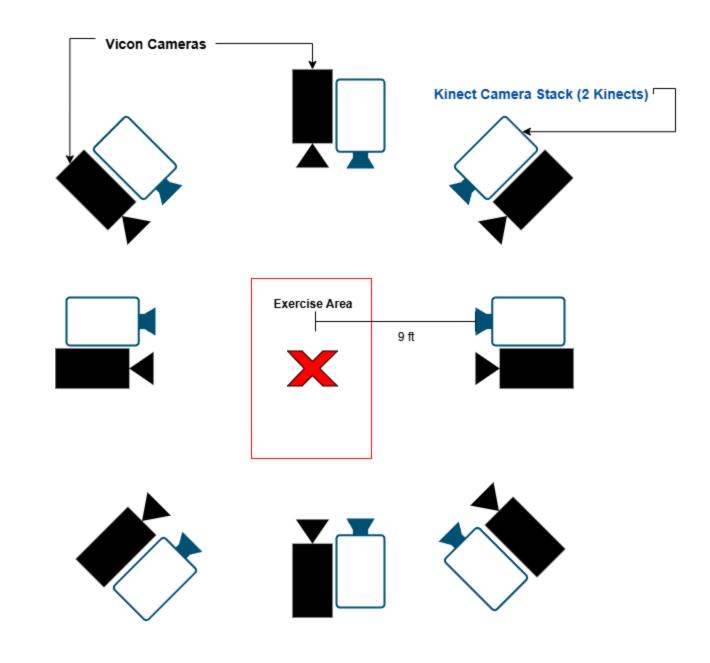


SECTION 5



Vicon System Overview

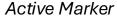
- Used Vicon as ground truth for joint position estimation
- Had 8 Vicon T160 cameras:
 - Greater horizontal FOV than vertical. 54 vs 39.7 deg
 - Placed at optimal heights and angles to minimize occlusions
 - Standard Operating at 790nm
- Marker labelling done in Nexus2.16 software
- Used built in interpolation functions to estimate occluded marker positions

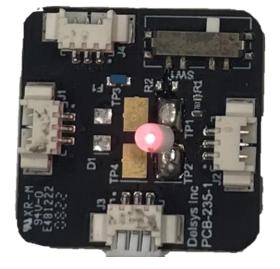




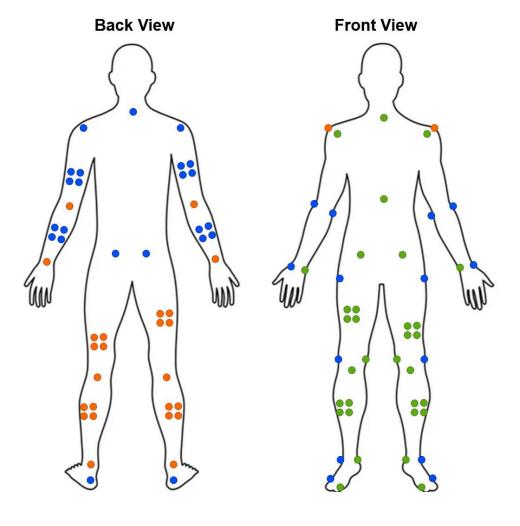
Vicon Marker Placement & Joint Estimation

- Markers placed according to International Society of Biomechanics (ISB) standards
- Using marker group centroids to find joints
- Marker clusters attached to improve interpolation accuracy
- Used custom 740nm active LED markers to avoid interference with Kinect TOF sensor
 - Kinect operates at 850nm
 - Vicon T160 operates at 790nm
- Two marker sets used, optimized for visibility during different exercises





Marker set Diagram









Data Collection

Study Overview

- •Subjects:
 - 15 non-military controls with no MSKIs in the past 12 months
 - Even M/F proportions
- Each subject performed 27 different exercises
- Exercises repeated at 2 camera heights
- •Goal:
 - Assess body tracking systems' performance across varied body types, exercises, and camera heights using Vicon as the reference
 - Validate real-time Medic outcomes
 - Test Sapiens as an alternative
 - Obtain a corpus of data to be used for future studies

Exercises (MEDIC Exercises)	Outcomes Tracked
Single Leg Balance	Trunk Lateral Tilt, Trunk Forward Tilt, Knee Abduction
Double Leg Squat	Trunk Lateral Tilt, Trunk Forward Tilt, Hip Flexion, Knee Flexion, Foot Height
Forward Lunge	Trunk Lateral Tilt, Trunk Forward Tilt, Postural Sway, Balance Time
Prisoner Jump Squat	Knee Flexion
Side Hop To Balance	Trunk Lateral Tilt, Knee Abduction, Knee Flexion, Rep Count
Overhead Press	Knee Flexion, Knee Distance, Hip Flexion, Trunk Forward Tilt, Trunk Lateral Tilt, Trunk Tibia Alignment
Hex Bar Deadlift	Knee Flexion, Hip Flexion, Trunk Lateral Tilt, Trunk Forward Tilt, Leading Knee Past Ankle
Plank	Knee Flexion, Hip Flexion, Trunk Forward Tilt, Trunk Lateral Tilt, Knee Distance, Foot Height
Push Up	Trunk Lateral Tilt, Knee Flexion, Lateral Jump Distance
Double Leg Stance	Trunk Lateral Tilt, Trunk Forward Tilt, Pelvis Lateral Tilt
Tandem Stance	Knee Flexion, Hip Flexion, Trunk Forward Tilt, Trunk Lateral Tilt, Foot Height, Knee Distance, Leading Knee Past Ankle
Standing Knee Flexion	Trunk Lateral Tilt, Trunk Forward Tilt, Hop Distance
March In Place	Knee Flexion, Trunk Forward Tilt, Trunk Tibia Alignment
Ice Skater	Wrist Height Over Shoulder, Trunk Lateral Tilt, Trunk Forward Tilt, Elbow Flexion, Hip Flexion, Knee Flexion, Wrist Past Ankle
Single Leg Reach	Foot Height, Knee Flexion, Pelvis Stability, Trunk Lateral Tilt
L Hop	Knee Flexion, Trunk Forward Tilt, Trunk Lateral Tilt, Ankle Distance
Step Up	Knee Flexion, Trunk Forward Tilt, Trunk Tibia Alignment, Hip Flexion
Hurdle Step	Knee Flexion, Trunk Forward Tilt, Trunk Lateral Tilt, Trunk Tibia Alignment, Hip Flexion, Knee Distance
Y-Balance Test	Knee Flexion
Barbell Deadlift	Knee Extension, Rep Count
Heel Slide	Trunk Lateral Tilt, Rep Count, Task Time
Knee Lift	Hip Height, Pelvis Lateral Tilt
Sit To Stand	Single Leg Hip Flexion, Pelvis Lateral Tilt, Foot Height
Single Leg Bridge	Trunk Forward Tilt, Elbow Flexion, Hip-Center Displacement, Hip Flexion, Knee-Center Displacement
Straight Leg Raise	Knee Height, Elbow Shoulder Alignment, Trunk Lower body Alignment
Side Plank	Knee Flexion, Hip Flexion, Elbow Flexion, Hip-Center Displacement, Trunk Forward Tilt
Hand Release Push Up	Trunk Lower body Alignment, Elbow Flexion, Knee Height

Protocol Summary

Briefing

• Subjects familiarized with all exercises prior to recording

Markers

• 69 active LED markers applied to subjects

Marker-set changed mid-collection

Exercises

• 5 reps per set

• 27 exercises, 56 total sets

Finish

Total time ~3.5 hours



Capture Timeline

- Data Collection every day for 3 weeks
- Processing data in-between collections

Day#	Task	Time Estimate	
Day –1	Familiarize subject	15 min	
Day 0	Data Collection	5 hours	
Day 0 Transfer data from PC to Candor DC-1 server		5 hours	
Day 0 to 1	Kinect file sorting on Candor DC-1 server	1 hour	
Day 0 to 1	Sapiens pipeline and lift3D	10 hours	
Day 0 to 1	MEDIC pipeline	30min – 1 hour	
Day 1	Vicon annotation	2-4 hours	
Day 2	Biomechanics pipeline	30min – 1 hour	





Data Analysis Pipeline

Input Alignment Obstacles

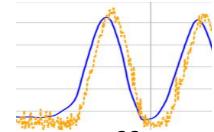
- Inputs
- Vicon Marker Trajectories 100Hz
- Sapiens Joint Trajectories 60Hz
- Medic Timeseries Metric Outcomes 60Hz

Challenges:



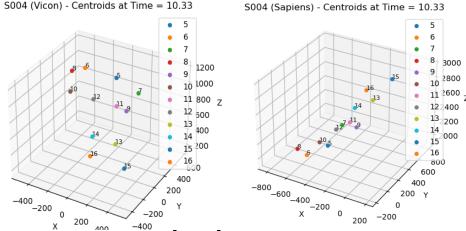
Sampling Rate

- Vicon: 100Hz
- MEDIC and Sapiens: 60Hz



Time Offset

- Kinect and Vicon cameras controlled separately
- MEDIC capture starts after body scan



Spatial Alignment

 Vicon and Kinect have different coordinate systems



Errors in Existing Biomechanics Pipeline

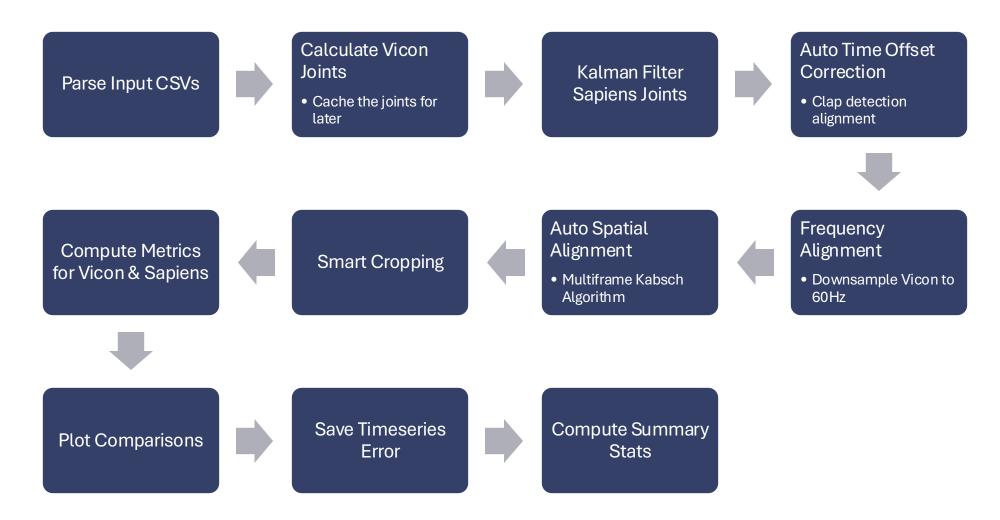
Existing Biomechanics Pipeline Overview:



- Auto-spatial alignment failed due to temporal misalignment
- Extensive manual input -> prolonged processing time and constant human supervision
- No applicability across different exercises & metrics
- Used 'vicon planes' rather than body-defined planes for kinematics calculations
- •Ended up largely writing new pipeline from scratch



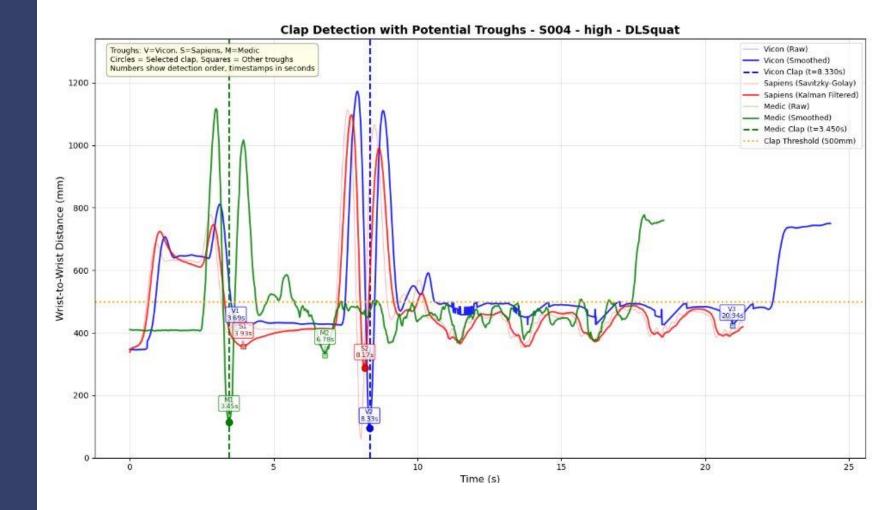
Sapiens Medic Validation Pipeline Operations Overview





Clap Based Time Alignment

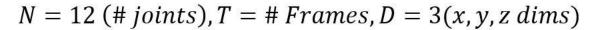
- Clap at exercise start
- Distinct clap events are detected
- Savitsky Golay filtering applied to get clear peaks
- Kalman filtering induces a time offset and flattens peaks:
 - Initial search window is identified using Savitsky Golay filtered data
 - Final clap detection refined with Kalman filtered data
- Potential troughs labelled



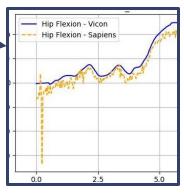


Improved Spatial Alignment: Multi-frame Kabsch Algorithm

- Fully temporally aligned before spatial alignment
- Middle 20% of frames used for joint input
 - Using multiple frames reduced noise effects
 - Sapiens less accurate in initial frames. Middle is the most reliable
 - Alignment most important during the exercise (middle of the capture).
 - Kabsch Algorithm
 - Minimizes RMSE between two paired sets of points
 - Stack frames as one tall matrix input
 - No scaling factor used testing raw distance accuracy
 - o If det(R)<0, flip the sign of the rightmost right singular vector $(V_{2,4T,3})$ and recompute R to prevent reflections



$$P = Sapiens Joints \in \mathbb{R}^{(0.2 \cdot T \cdot N) \times 3}$$



$$Q = ViconJoints \in \mathbb{R}^{(0.2 \cdot T \cdot N) \times 3}$$

$$C = (P)^{\mathsf{T}} Q$$

$$C = U\Sigma V^{\mathsf{T}}$$

$$R = V^{\mathsf{T}}U \in \mathbb{R}^{3 \times 3}$$

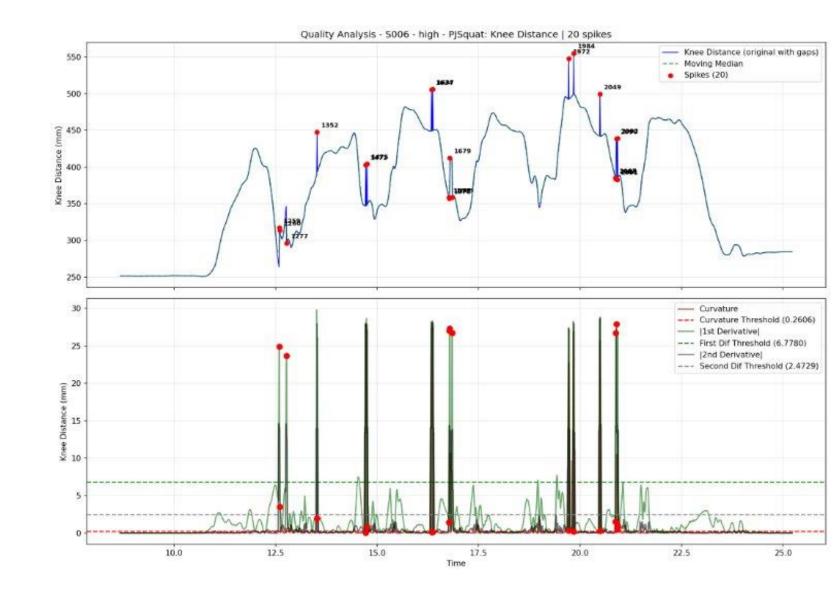
$$t = \bar{q} - R\bar{p}$$

$$SapiensAligned = P_{aligned} = RP + t$$

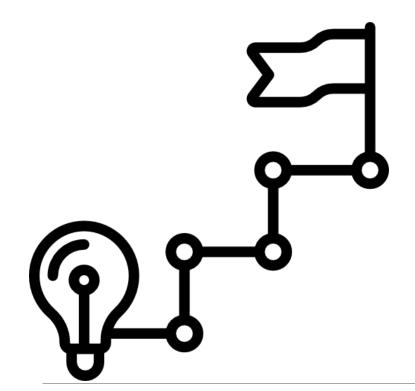


Vicon Quality Inspection

- The largest bottleneck of analysis was Vicon annotation
- Automates error detection process
- Detection methods:
 - 1st and 2nd Derivative
 - Curvature
 - Moving absolute median deviation
- Adaptive thresholds
- Indicates anomaly frames on plots
- Modular detection methods and thresholds







Results

SECTION 8



MHSRS Poster

- •Work from the study was presented in a poster format at the Military Health System Research Symposium (MHSRS) on August 4-7, 2025
- The poster detailed conclusions drawn about the validation of the MEDIC system's accuracy when computing spatial and angular feedback metrics as compared to Vicon ground truth

System Evaluation of "Optical Screening and Conditioning for Injury Resilience"

Shiwani^{1,2}, Nikolas Lamb^{1,2}, Amy Silder³, Nicole M. Donahue^{1,2}, Dan Clapp^{1,2}, Casey Knox^{1,2}, Helen Huang^{1,2} Brian Green^{3,4}, Serge H. Roy^{1,2}, Gianluca De Luca^{1,2}, Joshua C. Kline^{1,2} ¹Altec Inc., Natick, MA; ²Delsys Inc., Natick, MA; ²Naval Health Research Center San Diego, CA; ⁴Leidos, Inc., San Diego, CA



INTRODUCTION

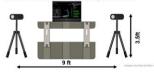
- Military Need: Musculoskeletal injuries (MSKIs) are a leading cause of disability among warfighters (>700,000 injuries; 2.4 M health visits annually)
- Mission: Improve MSKI resiliency by identifying and correcting high-risk movement patterns during screening and conditioning exercises using a realtime biofeedback device for movement quality.
- Device Description: OSCIR (Optical Screening and Conditioning for Injury Resilience) is a TRL 6 camerabased portable feedback device for autonomous MSKI screenings and assessments in operational and clinical settings.
- Study Description: Movement quality outcomes from OSCIR were validated against marker-based motion capture (MXT160, Vicon Systems, Oxford UK) among n=13 adults (8M/5F, 22-36y) during 9 exercises across several movement screening batteries (e. g. DIME, ACFT and other balance tests)

SYSTEM ARCHITECTURE

- Software Architecture: Uses parallel programming techniques and an open-source point cloud (PC) processing library for 3D visualization through Augmented Reality (AR) overlay of joint positions in
- Graphical User Interface: Clinically relevant outcomes reflecting key Go - No Go form corrections (based on a pre-selected threshold) are displayed in real-time (e.g., side-to-side lean forward bending, and collapsed knees during Double Leg Squat).



OSCIR Setup: Laptop; N=2 Red Green Blue-Depth (RGB-D) camera arrays (Frame Rate = 60Hz, Field-Of-View ≥180°, Size = 2x3x4 inch); Case/Table



METHODS: VALIDATION STUDY











RESULTS

Spatial Outcome	Exercises	Error (mean ± SD)
Knee Valgus	DLS, SHB, DL, PJS	1.52 ± 2.02 cm
Lead Knee Past Foot	FL, SHB	4.78 ± 3.95 cm
Foot Height	SLB, SHB, PJS	4.75 ± 4.22 cm
Dowel (Wrist) Height Over Clavicle	OHP	2.89 ± 2.00 cm
Dowel (Wrist) Past Feet	OHP	3.78 ± 4.45 cm
Knee Alignment	PLK, PU	1.37 ± 1.40 cm
Hip Alignment	PLK, PU	1.60 ± 1.48 cm
Trunk-Tibia Alignment	DLS, DL	5.55 ± 3.91 cm

CONCLUSION

- OSCIR resulted in relatively high accuracy for angular and spatial feedback metrics across all exercises.
- Applicability to Medical Care: OSCIR provides an autonomous injury screening and assessment tool that can be used in clinicianout-of-the-loop operational environments and embedded clinics.
- Impact on the Warfighter: OSCIR will assist key military stakeholders to manage MSKIs in warfighters by automating training and rehabilitation test batteries through real-time biomechanical feedback, making quantitative feedback more readily accessible and accurate

Angular Outcome	Exercises	4.03 ± 3.97°	
Knee Flexion	DLS, SLB, FL, SHB, OHP, PJS		
Trunk Flexion	DLS, SLB, FL, PLK, PU, DL, SHB, OHP, PJS	1.78 ± 1.72°	
Trunk Lateral Tilt	DLS, SLB, FL, SHB, OHP, DL, PJS	1.16 ± 1.21°	
Hip Flexion	DLS, SLB, FL, PLK, PU, DL, SHB, OHP, PJS	4.28 ± 4.46°	
Elbow Flexion	OHP, PLK, PU	5.69 ± 5.25°	

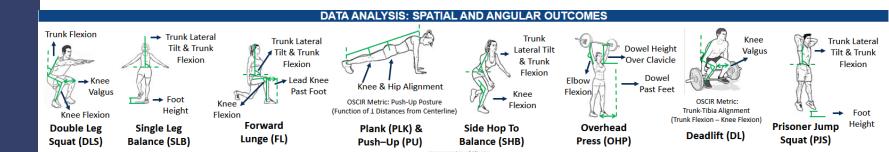
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Statistics

- Both spatial and angular metrics display relatively low error (< 5° or < 5 cm) across all exercises
- Both spatial and angular metrics display relatively low standard deviation (< 5° or < 5 cm)
- These results convey that MEDIC is accurate when producing outcomes



RESSETS					
Spatial Feedback Metrics			Angular Feedback Metrics		
Spatial Outcome	Exercises	Error (mean ± SD)	Angular Outcome	Exercises	Error (mean ± SD)
Knee Valgus	DLS, SHB, DL, PJS	1.52 ± 2.02 cm	Knee Flexion	DLS, SLB, FL, SHB,	4.03 ± 3.97°
Lead Knee Past Foot	FL, SHB	4.78 ± 3.95 cm		OHP, PJS	
Foot Height	SLB, SHB, PJS	4.75 ± 4.22 cm	Trunk Flexion	DLS, SLB, FL, PLK, PU,	1.78 ± 1.72°
Dowel (Wrist) Height	OHP	2.89 ± 2.00 cm		DL, SHB, OHP, PJS	
Over Clavicle			Trunk Lateral Tilt	DLS, SLB, FL, SHB,	1.16 ± 1.21°
Dowel (Wrist) Past Feet	OHP	3.78 ± 4.45 cm		OHP, DL, PJS	
Knee Alignment	PLK, PU	1.37 ± 1.40 cm	Hip Flexion	DLS, SLB, FL, PLK, PU,	4.28 ± 4.46°
Hip Alignment	PLK, PU	1.60 ± 1.48 cm		DL, SHB, OHP, PJS	
Trunk-Tibia Alignment	DLS, DL	5.55 ± 3.91 cm	Elbow Flexion	OHP, PLK, PU	5.69 ± 5.25°

RFSUI TS



Broader Goals

- •Outside of the scope for our summer work, there are some pathways the team intends to explore:
 - Optimal camera count
 - > How does accuracy degrade as viewpoints are lost? How many cameras are necessary for accurate capture?
 - Relevance of musculoskeletal constraints
 - > How does imposing musculoskeletal constraints impact body tracking?
 - Monocular 3D joint localization with a 2D camera
 - > Is it feasible to train a body tracking model to predict 3D joint locations from a single perspective?
 - Finetune Sapiens
 - Finetune the base model of sapiens for 3D pose estimation
 - Kinect replacement
 - ➤ How important is each Kinect data channel? Microsoft no longer supports the Kinect, so are there other options we could use instead?



Skills Learned



Aidan Kimberley

- Handling large datasets
 - Statistical analysis
- Biomechanics calculations
 - Algorithm development
- Human motion capture studies



Ethan Matzek

- Managing large multimodal systems
 - Bash Scripting
- Debian Packaging and Cmake
- Performing human studies
 - Vicon Nexus



Ava Megyeri

- 3D Reconstruction
 - Bash Scripting
- Computer Vision
- Algorithm Development





Acknowledgements





Thank you Delsys/Altec! /LTEC

