

ABSTRACT

TITLE: OpenPose module and machine learning classifier approach to detect toe-walking: a pilot study

AUTHORS: Giulio Valagussa^{1,2,3,*}, Luca Emanuele Molteni^{4,*}, Martina Boccotti², Giulia Purpura³, Cecilia Perin³, Alessandro Crippa⁴, Giuseppe Andreoni^{4,5}, Enzo Grossi², Daniele Piscitelli^{3,6}

PRESENTING AUTHOR: Giulio Valagussa

AFFILIATIONS: ¹PhD Program in Neuroscience, University of Milano-Bicocca, Milan, Italy; ²Villa Santa Maria SCS, Autism Research Unit, Tavernerio (CO), Italy; ³University of Milano-Bicocca, School of Medicine and Surgery, Milan, Italy; ⁴Scientific Institute IRCCS "E.Medea" Bosisio Parini, Lecco, Italy; ⁵Department of Design, Politecnico di Milano, Milan, Italy; ⁶Department of Kinesiology, University of Connecticut, Storrs, CT, USA; * *These authors are both first authors*

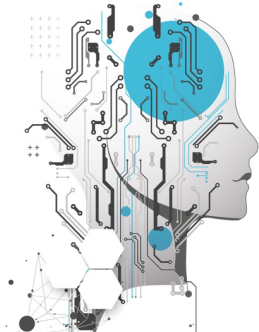
TOPICS: Autism Spectrum Disorder (ASD); Markerless gait analysis; Machine learning; toe-walking

Structure the contribution according to the following sections:

OBJECTIVES: This study aimed to develop a novel method for detecting toe-walking (TW) using the OpenPose module.

MATERIALS: The present study involved 15 subjects with neurotypical development (mean age 10.3 ± 3.1 years; age range: 6.5–16.1 years; 6 males) who simulated TW. We used the OpenPose module to extract the skeletons.

METHOD: All participants were administered a validated video-based coding protocol using standardised video recordings to quantify toe-walking¹. The test consisted of transporting an object (e.g., Lego®) from a physiotherapist to a playing table located 3 meters away and back again 10 times. All tests were conducted without shoes, with socks¹. Sagittal-plane video recordings of the walking trials were collected for each participant. Skeletons were extracted in the sagittal plane via the OpenPose module², and gait kinematics were computed. The TWIST algorithm was applied to identify the most



significant features and create two balanced subsets to optimise the training of various machine learning algorithms. These selected features were used to train supervised neural networks (NNs), which were evaluated for accuracy, sensitivity, specificity, and area under the curve (AUC)³.

RESULTS: A total of 1,793 steps, including 825 tip-toe gait samples, were used to train four neural network classifiers based on 14 selected features. These included three biomechanical dimensions: spatial (n=2; vertical distances between the malleolus and toes), angular (n=11; joint angles and range of motion at the hip, knee, and ankle, plus toe-off alignment angles), and temporal (n=1; stance phase duration) features. Performance was evaluated using leave-one-out cross-validation, repeated 19 times. The Support Vector Machine (SVM) classifier achieved the best performance, with an accuracy of 89.8%, sensitivity of 94.8%, specificity of 95.1%, and an AUC of 0.944. K-Nearest Neighbors (KNN) showed comparable results, with 89.4% accuracy, 93.0% sensitivity, 96.4% specificity, and an AUC of 0.935. The Bayesian classifier followed with 84.9% accuracy, 88.6% sensitivity, 96.3% specificity, and an AUC of 0.932. Random Forest (RF) yielded the lowest performance, with 54.6% accuracy, 57.3% sensitivity, 97.3% specificity, and an AUC of 0.598.

DISCUSSION: This pilot study demonstrates that a markerless gait analysis system using the OpenPose module combined with machine learning classifiers can accurately detect TW in children.

CONCLUSIONS: The proposed method offers the potential for automated detection and quantification of toe walking in standardised protocols and settings. The following research steps will be dedicated to studying a larger group of subjects to validate the findings of this preliminary study further and in other populations.

References

1. Valagussa G, Purpura G, Balatti V, Trentin L, Signori A, Grossi E. Quantitative assessment of tip-toe behavior in individuals with autism spectrum disorder and intellectual disability: A cross-sectional study. *Autism Res.* 2024 Feb;17(2):311-323. doi: 10.1002/aur.3072. Epub 2023 Dec 18. PMID: 38108559.
2. Molteni LE, Andreoni G. Comparing the Accuracy of Markerless Motion Analysis and Optoelectronic System for Measuring Gait Kinematics of Lower Limb. *Bioengineering (Basel).* 2025 Apr 16;12(4):424. doi: 10.3390/bioengineering12040424. PMID: 40281784; PMCID: PMC12025091.
3. Saeys Y, Inza I, Larrañaga P. A review of feature selection techniques in bioinformatics. *Bioinformatics.* 2007 Oct 1;23(19):2507-17. doi: 10.1093/bioinformatics/btm344. Epub 2007 Aug 24. PMID: 17720704.