Whole body gait analysis using depth camera and machine learning differentiates subjects with anterior cruciate ligament reconstruction from healthy controls

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INTRODUCTION: Since gait is a highly coordinated whole-body movement, gait spontaneously reflects conditions of the musculoskeletal and nervous systems. Recent advancement of technologies allows an ease of capture of whole-body movement and generation of algorithms by machine learning. Thus, we hypothesized that machine learning of whole-body movement during gait could detect a slight change in conditions in the musculoskeletal and nervous systems. The current study tested this hypothesis by focusing on subjects who restored knee instability and sports activity by the reconstruction of anterior cruciate ligament (ACL). Even after successful ACL reconstruction, gait features related to ACL injury might remain. So, the purpose of the current study is to determine whether machine learning of whole-body movement during gait can differentiate subjects with ACL reconstruction from healthy controls.

METHODS: 31 healthy subjects (mean 42.0±14.2 years) and 27 subjects (mean 36.9±10.9 years) who had returned to sports at least 1 year after ACL participated in the study. Tibial translational motion was quantified by the KT-1000 and three-dimensional (3D) motion analysis (point cluster method) on a 10-m straight gait. Each gait was also captured by the depth camera (Kinect, Microsoft) to generate the positional information of 25 skeletal points in a whole body. Based on the 300 segments determined by two joint points, 2700 features were generated (300 segments × 3 axes × 3 statistics), followed by selection of 20 gait features strongly correlated with ACL reconstruction with 4 types of correlation analysis. Binarry classification learning using 22 different algorithms was performed to discriminate subjects with ACL reconstruction from healthy subjects. Algorithm performance was evaluated by Leave-One-Out cross-validation with calculations of the Mathews correlation coefficient (MCC), sensitivity, and specificity.

RESULTS: The measurement by the KT-1000 and 3D-motion analysis showed no significant difference in anterior translation of tibia between the ACL reconstructed knees and the healthy knees (Figure 1), indicating that the ACL reconstruction restored the anterior stability of the injured knees. The algorithm × parameters generated 24716 different learned models. The highest MCC, sensitivity, and specificity of the generated learning models were 0.742 (0.260 ± 0.159, all model average ± standard deviation), 0.963 (0.599 ± 0.147), and 0.774 (0.657 ± 0.071), respectively, suggesting that gait after ACL reconstruction shares some features different from gait of healthy controls and that subjects with ACL reconstruction can be predicted with gait analysis. Among selected 20 gait features related to ACL reconstruction, positioning features of ipsilateral [hand-elbow] and contralateral [hand-hand] contributed to the prediction more than other features (Figure 2), suggesting the motions in hands might reflect knee conditions more than previously thought.

DISCUSSION: These findings indicate that, even after returning to sports activity with restored ACL function, the gait of subjects with ACL reconstruction is different from that of healthy subjects in terms of whole-body movement. This might be due to neuromuscular strategies that increase the risk of ACL injury, residual compensatory movements after ACL injury, and subclinical knee dysfunction. Further, the findings suggest that a comprehensive analysis of whole-body movement during gait with machine learning is a powerful method to analyze gait features derived from musculoskeletal conditions and that this method may contribute to the development of a novel prediction system for diseases that affect gait function.

SIGNIFICANCE/CLINICAL RELEVANCE: A combination of machine learning with whole-body motion analysis can identify subtle gait features derived from subclinical conditions that affect gait function.

Figure 1

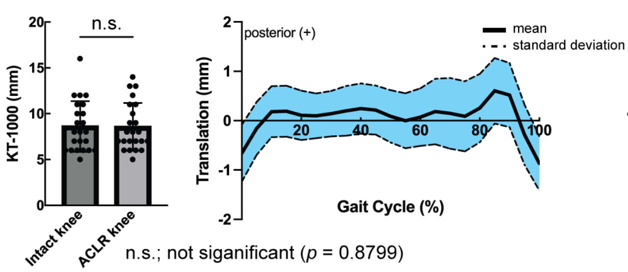

Figure 2