Inertial Sensor based Gait Analysis Discriminates Subjects with and without Visual Impairment Caused by Simulated Macular Degeneration

Christoph M. Kanzler[1], *Student Member, IEEE, EMBS*
Jens Barth[2], Jochen Klucken[3], Bjoern M. Eskofier[1], *Member, IEEE, EMBS*

***Abstract*— Macular degeneration is the third leading cause of blindness worldwide and the leading cause of blindness in the developing world. The analysis of gait parameters can be used to assess the influence of macular degeneration on gait.**

This study examines the effect of macular degeneration on gait using inertial sensor based 3D spatio-temporal gait parameters. We acquired gait data from 21 young and healthy subjects during a 40 m obstacle walk. All subjects had to perform the gait trial with and without macular degeneration simulation glasses. The order of starting with or without glasses alternated between each subject in order to test for training effects. Multiple 3D spatio-temporal gait parameters were calculated for the normal vision as well as the impaired vision groups.

The parameters trial time, stride time, stride time coefficient of variation (CV), stance time, stance time CV, stride length, cadence, gait velocity and angle at toe off showed statistically significant differences between the two groups. Training effects were visible for the trials which started without vision impairment. Inter-group differences in the gait pattern occurred due to an increased sense of insecurity related with the loss of visual acuity from the simulation glasses.

In summary, we showed that 3D spatio-temporal gait parameters derived from inertial sensor data are viable to detect differences in the gait pattern of subjects with and without a macular degeneration simulation.

We believe that this study provides the basis for an in-depth analysis regarding the impact of macular degeneration on gait.

I. INTRODUCTION

Macular degeneration is the third leading cause of blindness worldwide and the leading cause of blindness in the developing world [1].

Drusen are protein based deposits under the retina and are the most characteristic physical sign of macular degeneration. They can damage the retinal pigment epithelium which can lead to retinal atrophy [2]. Several risk factors like advancing age, genetic factors, white race [2] or a history of smoking [3] can increase the likelihood of a disease outbreak.

At the moment, there is no effective cure for macular degeneration. However, different therapies including antioxidant supplementation, lifestyle and dietary modifications as well as vitreoretinal surgery can help to limit the damage of the disease [2].

An early diagnosis is vital to limit healthcare costs and to decrease the impact of the disease. Possible early indicators for a starting visual impairment could be alterations in the postural stability or in the gait pattern of the patients.

Anand et al. [4] already showed that the postural stability decreases in patients with cataract and refractive blur. Durmus et al. [5] reported that especially the gait parameters gait velocity and cadence increase after a gain in visual acuity associated with a cataract surgery. Yamaji et al. [6] examined the impact of light-scattering glasses and the thereby induced loss in visual acuity on obstacle gait. They reported a significant change in various spatio-temporal gait parameters between the groups with and without the glasses, e.g. the stride length and the stride time. Even though the influence of cataract [5] or light-scattering glasses [6] can't be directly compared to the effects of a macular degeneration, all of those disabilities lead to a decrease in visual acuity. We therefore assume that macular degeneration could also have effects on the gait pattern of the patient. To our knowledge, no study has analyzed the influence of macular degeneration on gait using 3D spatio-temporal gait parameters yet.

The purpose of the present study was to examine the effect of macular degeneration on gait. We therefore calculated 3D spatio-temporal gait parameters for a group of young subjects which performed a 40 m obstacle walk with and without macular degeneration simulation glasses. Inertial sensors were used for gait parameter calculation to allow a mobile and unobtrusive gait assessment.

We believe that this study provides the basis for an in-depth analysis regarding the impact of macular degeneration on gait.

II. METHODS

A. Inertial Sensor Platform

A Shimmer®3 (Shimmer, Dublin, Ireland) inertial sensor platform was attached at the lateral ankle of each foot (see Fig. 1). Gait data was recorded by a 3D accelerometer (range ± 8 g, resolution 12 bit) and a 3D gyroscope (range ± 1000 dps, resolution 16 bit) at a sampling rate of 102.4 Hz.

B. Study Protocol

Data from 21 young subjects (see subject characteristics in Table I) was collected at ASTRUM IT GmbH (Erlangen, Germany). All subjects were advised to perform a 40 m walk with obstacles. The 40 m walk was carried out on a straight

This work was funded by the Bavarian Research Foundation (AZ 974-11) and by a project grant of ASTRUM IT GmbH. The research study was supported in parts by the EFIMoves project of the FAU Emerging Fields Initiative. The authors declare no conflict of interest.

[1]C. M. Kanzler, B. M. Eskofier are with the Digital Sports Group, Pattern Recognition Lab, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Germany.

[2]J. Barth, is with the ASTRUM IT GmbH, Erlangen, Germany.

[3]J. Klucken is with the University Hospital Erlangen, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Germany.

Corresponding author: C. M. Kanzler (e-mail: christoph.kanzler@fau.de).

Fig. 1. A Shimmer®3 inertial sensor platform was mounted on the lateral side of each foot.

Fig. 2. All subjects had to wear specific glasses[1] as a simulation for a macular degeneration.

10 m track. One rectangular box 12 cm high was placed 4.5 m after the start of the track. Another box 24 cm high was placed at a distance of 2.6 m from the first box and was used as an additional obstacle.

Trials had to be completed with and without the macular degeneration glasses (see Fig. 2). A trial was defined as an obstacle walk of one specific subject. The order of starting with or without glasses alternated between each subject in order to test for training effects. The participants were instructed to look directly through the glasses and move their head and not only their eyes if they want to look at the ground. This ensured that the subjects could not neglect the effect of the glasses by not looking directly through them. The manufacturer[1] did not publish any quantifiable information about the loss of vision implied with the glasses.

All participants did already know the acquisition environment prior to this study. The room illumination conditions did not change during the data recording. Written informed consent was obtained prior to the data collection. All experimental procedures were conducted in accordance with the declaration of Helsinki.

C. Definition of Gait Parameters

The following gait parameters as well as the trial time were calculated for data analysis.

The stride time was defined as the time between two subsequent heel strikes (HS) of the same foot whereas the swing time was the time between the toe off and the heel strike of the same foot. Furthermore, the stance time was determined as the time between the heel strike and the toe off of the same foot. The stride length was the distance between two consecutive mid stances of the same foot. In addition, the gait parameter cadence and gait velocity were calculated. The 3D gait parameters sagittal angle at heel strike (angle HS) and at toe off (angle TO) as well as the maximum toe clearance (max. TC) were estimated.

The gait events heel strike, toe off and mid stance were determined using an accelerometer and gyroscope based peak detection [7], a zero crossing detection in the gyroscope [8] and a energy based method [9] respectively. The stride length was estimated using gravity cancellation as well as double dedrifted integration according to Rampp et al. [7]. The shoe size independent approach for 3D gait parameter calculation from Kanzler et al. [10] was applied to assess the toe clearance and the foot angle.

[1]"Produkt + Projekt" , Wolfgang Moll, http://www.produktundprojekt.de/alterssimulationsanzug/augenerkrankungen.html

TABLE I
SUBJECT CHARACTERISTICS FOR SUBJECTS WITH AND WITHOUT VISION IMPAIRMENT (VI). AGE, HEIGHT AND WEIGHT IN MEAN ± STANDARD DEVIATION.

Characteristic	Start without VI	Start with VI	Overall
N	11	10	21
Sex [m/f]	9/2	7/3	16/5
Age [y]	33.1 ± 9.9	33.0 ± 11.6	33.0 ± 10.5
Height [cm]	180.5 ± 5.8	177.7 ± 6.7	179.1 ± 6.2
Weight [kg]	78.6 ± 11.2	79.4 ± 6.4	79.0 ± 9.0

D. Evaluation Concepts

In order to find differences between visual impaired gait and normal gait, we calculated the mentioned gait parameters for both groups separately. Additionally, subgroups were created depending on whether the subject started with or without vision impairment in order to assess training effects.

For all gait parameters the mean, standard deviation and coefficient of variation (CV = standard deviation divided by the mean) were calculated for each group. A paired t-test was used to test for statistically significant differences between the groups. Statistical analysis was done in MATLAB R2015a (MathWorks Inc., Natick, MA, USA).

Gait parameters were calculated with a JAVA (Oracle, Redwood City, CA, USA) framework of the ASTRUM IT GmbH in version 1.5. This framework used the multi-dimensional subsequence dynamic time warping approach from Barth et al. [11] for segmenting single strides out of the continuous signal. The method did not detect turning strides but only regular straight strides. After the stride segmentation, the above mentioned gait parameters were calculated for each stride and subsequently averaged over all strides of a trial.

III. RESULTS

Table II presents the group specific (normal and impaired vision) gait parameters for the 40 m obstacle walk. Table III and IV show gait parameters for all trials which started with

TABLE II
GAIT PARAMETERS AVERAGED OVER **ALL** 40 M OBSTACLE WALKS. SIGNIFICANT ENTRIES ARE IN BOLD FACE.

Parameter	Normal Vision		Impaired Vision		
	Trials: 18		Trials: 18		
	Mean	Std	Mean	Std	p-Value
Trial Time [s]	33.04	2.92	35.10	2.51	**0.01**
Stride Time [s]	1.14	0.09	1.16	0.09	0.22
Stride Time CV	12.08	2.08	13.33	2.25	**0.01**
Swing Time [s]	0.42	0.03	0.42	0.03	0.82
Swing Time CV	19.18	3.61	21.24	4.67	0.20
Stance Time [s]	0.72	0.07	0.74	0.07	0.12
Stance Time CV	16.57	2.16	18.05	3.54	**0.04**
Stride Length [cm]	164.83	13.30	155.58	15.84	**0.01**
Stride Length CV	15.86	6.17	17.49	3.58	0.31
Cadance [1/min]	52.93	4.63	52.14	4.11	0.20
Gait Velocity [m/s]	1.46	0.13	1.36	0.12	**0.01**
Angle HS [°]	17.75	5.88	16.17	4.65	0.11
Angle TO [°]	−76.97	3.68	−75.11	3.45	**0.01**
Max. TC [cm]	19.08	3.81	18.58	2.42	0.48

TABLE III
GAIT PARAMETERS AVERAGED OVER THE 40 M OBSTACLE WALKS, WHICH STARTED **WITH** VISION IMPAIRMENT. SIGNIFICANT ENTRIES ARE IN BOLD FACE.

Parameter	Normal Vision		Impaired Vision		
	Trials: 9		Trials: 9		
	Mean	Std	Mean	Std	p-Value
Trial Time [s]	32.42	2.68	35.93	2.33	**0.01**
Stride Time [s]	1.09	0.09	1.14	0.10	**0.03**
Stride Time CV	12.36	2.31	14.04	2.18	**0.01**
Swing Time [s]	0.40	0.03	0.41	0.03	0.48
Swing Time CV	19.35	4.00	21.10	5.53	0.53
Stance Time [s]	0.69	0.08	0.73	0.07	**0.01**
Stance Time CV	16.65	2.56	18.59	3.36	**0.01**
Stride Length [cm]	158.17	8.91	145.89	10.74	**0.01**
Stride Length CV	14.54	4.73	17.93	3.50	0.15
Cadance [1/min]	55.25	4.86	53.13	4.73	**0.03**
Gait Velocity [m/s]	1.46	0.10	1.30	0.08	**0.01**
Angle HS [°]	15.44	6.40	15.56	5.81	0.90
Angle TO [°]	−77.50	3.46	−74.72	3.05	**0.01**
Max. TC [cm]	17.50	2.52	17.28	2.09	0.81

TABLE IV
GAIT PARAMETERS AVERAGED OVER THE 40 M OBSTACLE WALKS, WHICH STARTED **WITHOUT** VISION IMPAIRMENT.

Parameter	Normal Vision		Impaired Vision		
	Trials: 9		Trials: 9		
	Mean	Std	Mean	Std	p-Value
Trial Time [s]	33.65	3.17	34.26	2.52	0.53
Stride Time [s]	1.19	0.07	1.18	0.07	0.43
Stride Time CV	11.81	1.92	12.62	2.22	0.32
Swing Time [s]	0.43	0.02	0.43	0.02	0.31
Swing Time CV	19	3.42	21.38	3.95	0.20
Stance Time [s]	0.76	0.06	0.75	0.06	0.51
Stance Time CV	16.49	1.83	17.51	3.83	0.41
Stride Length [cm]	171.50	14.02	165.28	14.36	0.15
Stride Length CV	17.18	7.39	17.04	3.81	0.95
Cadance [1/min]	50.61	3.13	51.15	3.35	0.42
Gait Velocity [m/s]	1.45	0.16	1.41	0.13	0.27
Angle HS [°]	20.06	4.53	16.78	3.36	0.06
Angle TO [°]	−76.44	4.02	−75.50	3.96	0.29
Max. TC [cm]	20.67	4.33	19.89	2.06	0.49

and without vision impairment respectively. Fig. 3 illustrates the behavior of the stride length given the different testing conditions.

Three trials had to be excluded from the data analysis because the stride segmentation could not detect enough valid strides.

The annotated results describe the mean and standard deviation values of all trial mean values. The trial mean value was calculated out of all strides belonging to this trial.

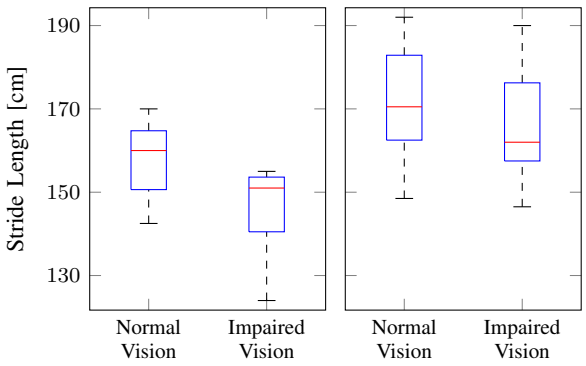
Independent of the order of wearing the simulation glasses, the trial time, stride time CV, stance time CV, stride length, gait velocity and sagittal angle at toe off showed statistically significant differences between the normal and impaired vision groups (see Table II). Regarding all trials which started with vision impairment, the already mentioned gait parameters as well as the stride time, stance time and cadence showed statistically significant differences (see Table III). For the trials which started without vision impairment, no gait parameters showed statistically significant differences (see Table IV).

A normalization of the gait parameters with respect to the height of the subject did not change the statistical significances of the results. Therefore, all presented results were not normalized.

IV. DISCUSSION

This study examined the influence of a macular degeneration simulation on gait of young subjects, who performed 40 m obstacle walks with and without the simulation glasses. Inertial sensors were used to calculate 3D spatio-temporal gait parameters for the normal vision and the impaired vision trials. The goal was to find differences in the gait pattern between both conditions.

The results for the 40 m obstacle walk in Table III suggest that multiple gait parameters (trial time, stride time, stride time CV, stance time, stance time CV, cadence, gait velocity, angle TO) can be used to distinguish between the normal vision and the impaired vision group. This makes also sense from a psychological point of view, as the subjects felt insecure due to their decreased visual acuity which resulted in uncertain gait. This insecurity was reflected in the calculated gait parameters: The subjects did smaller and slower strides which lead to increasing temporal and decreasing spatial gait parameters. Especially the stride length noticeably decreased between the normal (158.17 ± 8.91 cm) and the impaired vision group (145.89 ± 10.74 cm) while showing a statistically significant difference (p-value = 0.01). However, we could also detect severe training effects. If the subjects started without vision impairment, they already performed the 40 m walk once before they did the trial with the macular degeneration simulation. Therefore, they felt more secure during the second trial which neglected the effect of the glasses. Subsequently, no gait parameters (see Table IV) showed statistically significant differences between the groups. The inter-group difference in stride length did also decrease compared to the trials which started with vision



(a) Start **with** vision impairment. (b) Start **without** vision impairment.

Fig. 3. Box plot of the stride length for normal and impaired vision given a start with (a) and without (b) vision impairment.

impairment (see Fig. 3).

Yamaji et al. [6] reported similar results for an obstacle walk with light-scattering glasses. In their study, stride time, stance time, swing time, both limb stance times, stride length, step length, gait velocity as well as the step angle showed statistically significant differences between the normal and impaired vision groups. They also reported an increase in temporal gait parameters and a decrease in stride length, which confirms our hypothesis of insecurity due to loss of visual acuity and a resulting uncertain gait. However, they proved greater differences for several gait parameters between the groups than we did. For example, their stride time had an absolute difference of 0.35 ± 0.07 s, whereas we measured only 0.05 ± 0.01 s absolute change between the groups (see Table III). Interestingly, these inconsistent inter-group differences occurred despite a similar study population. We suspect that the main reason of the varying outcomes were the different obstacles used by Yamaji et al. [6] as they used three obstacles with different height. Additionally, their glasses could decrease the visual acuity even more than the glasses used in this study. Both factors could increase the insecurity and gait uncertainty of their subjects which could result in larger inter-group differences.

There are two major disadvantages of this study: First, the effect of the macular degeneration simulation glasses must be questioned. Definitely, they could not replace the effects of a real macular degeneration. Nevertheless, the subjects experienced insecurity and a loss of visual acuity while wearing the glasses. Additionally, the usage of simulation glasses allowed a meaningful comparison of inter-group differences because the same population could perform the normal and impaired vision trials. We therefore can assume that all inter-group differences result from the usage of the glasses as well as training effects which is not the case in a study design including a patient and a control population. Second, only young subjects were incorporated into the study. As macular degeneration is a age-related disease and also gait characteristics strongly alternate with increasing age, the executed experiments can not be directly transferred to real, elderly patients with macular degeneration. We assume that the difference in gait parameters between the groups would increase for elderly patients.

V. CONCLUSION

We presented a study which examined the effects of a macular degeneration simulation on obstacle gait using inertial sensor based gait parameters. Various spatio-temporal gait parameters showed statistically significant differences between the groups. We conclude that gait parameters are a viable indicator to discriminate between subjects with and without a macular degeneration simulation.

In the future, a study which includes patients with a real macular degeneration must be conducted as the simulation glasses could not fully mimic the symptoms of the real disease. Moreover, a classifier based on the presented gait parameters could be created to automatically distinguish between subjects with and without macular degeneration. Furthermore, the suitability of gait parameters as an early indicator for age-related macular degeneration could be examined.

REFERENCES

[1] S. Resnikoff, D. Pascolini, D. Etya'ale, I. Kocur, R. Pararajasegaram, G. P. Pokharel, and S. P. Mariotti, "Global data on visual impairment in the year 2002," *Bulletin of the World Health Organization*, vol. 82, no. 11, pp. 844–851, 2004.

[2] R. D. Jager, W. F. Mieler, and J. W. Miller, "Age-related macular degeneration." *The New England Journal of Medicine*, vol. 358, no. 24, pp. 2606–2617, 2008.

[3] R. Klein, T. Peto, A. Bird, and M. R. Vannewkirk, "The epidemiology of age-related macular degeneration," *American Journal of Ophthalmology*, vol. 137, no. 3, pp. 486–495, 2004.

[4] V. Anand, J. G. Buckley, A. Scally, and D. B. Elliott, "Postural stability changes in the elderly with cataract simulation and refractive blur," *Investigative Ophthalmology and Visual Science*, vol. 44, no. 11, pp. 4670–4675, 2003.

[5] B. Durmus, S. Emre, C. Cankaya, O. Baysal, and Z. Altay, "Gain in visual acuity after cataract surgery improves postural stability and mobility." *Bratislava Medical Journal*, vol. 112, no. 12, pp. 701–5, Jan. 2011.

[6] S. Yamaji, "Influence of degraded visual acuity from light-scattering goggles on obstacle gait," *Health*, vol. 03, no. 02, pp. 99–105, 2011.

[7] A. Rampp, J. Barth, S. Schülein, K.-G. Gaßmann, J. Klucken, and B. M. Eskofier, "Inertial sensor-based stride parameter calculation from gait sequences in geriatric patients," *IEEE Transactions on Biomedical Engineering*, vol. 62, no. 4, pp. 1089–1097, April 2015.

[8] A. Mannini and A. M. Sabatini, "A hidden markov model-based technique for gait segmentation using a foot-mounted gyroscope," in *Proceedings of the 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS)*, Boston, USA, 2011, pp. 4369–4373.

[9] I. Skog, H. Peter, J. Rantakokko, and J. Nilsson, "Zero-velocity detection in pedestrian navigation systems - an algorithm evaluation," *Biomedical Engineering*, vol. 57, no. 11, pp. 2657–2666, 2010.

[10] C. M. Kanzler, J. Barth, A. Rampp, H. Schlarb, F. Rott, J. Klucken, and B. M. Eskofier, "Inertial sensor based and shoe size independent gait analysis including heel and toe clearance estimation," in *Proceedings of the 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS)*, Milan, Italy, 2015, pp. 5424–5427.

[11] J. Barth, C. Oberndorfer, C. Pasluosta, S. Schülein, H. Gassner, S. Reinfelder, P. Kugler, D. Schuldhaus, J. Winkler, J. Klucken, and B. M. Eskofier, "Stride segmentation during free walk movements using multi-dimensional subsequence dynamic time warping on inertial sensor data," *Sensors*, vol. 15, no. 3, pp. 6419–40, Jan. 2015.