Development of independent locomotion in children with a severe visual impairment

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1. Introduction

According to the International Classification of Diseases there are four levels of visual function: normal vision, moderate visual impairment, severe visual impairment and blindness. Moderate visual impairment combined with severe visual impairment are grouped under the term “low vision”; low vision taken together with blindness represents all visual impairment (International Statistical Classification of Diseases and Related Health Problems, 10th Revision, Version, 2007). According to the World Health Organization, globally about 284 million people are visually impaired, of which 39 million are blind and 245 million have low vision.

A visual impairment can have a major impact on motor development and skill acquisition. In totally blind infants without evidence of brain damage, a delay in head control is observed at the age of two months, as well as abnormally exaggerated fidgety movements and prolonged periods of ataxia in postural control (Prechtl, Cioni, Einspieler, Bos, & Ferrari, 2001). A delayed onset of different motor milestones, such as sitting, crawling, standing and walking, is also reported in visually impaired infants (Elisa et al., 2002; Levitzon-Korach, Tennenbaum, Schnitzer, & Ornoy, 2000). Crawling on hands and knees is observed in 55% of blind children with mean age of onset of 15 (stdev 10) months (Elisa et al., 2002) while in children with normal vision 75–82% shows crawling on hands and knees by the age of 13 months 2 weeks (mean age of onset 8 months
2 weeks) (Martorell et al., 2006). Independent walking is only achieved at a mean age of 19 months 3 weeks (stdev 9 months 2 weeks) versus 12 months (stdev 1 month 3 weeks) in children with normal vision.

Whether, during development, multisensory integration and brain plasticity might overcome this initial delay is uncertain. In one study no differences were found in locomotion skills between 9 year old children with visual impairments and sighted children (Houwen, Visscher, Hartman, & Lemmink, 2007); another study reported on poor balance and coordination in 7 year old blind children (Navarro, Fukujima, Fontes, Matas, & Prado, 2004). Performance is likely dependent on the severity of the visual impairment, the properties of the task and changing environmental conditions (Houwen, Visscher, Lemmink, & Hartman, 2008) which can explain differences in performance in different studies. Considering different tasks, Houwen and co-workers (2008) showed that children with a visual impairment show poor performance on static and slow dynamic balance tasks but in fast dynamic balance tasks they perform as well as their normally sighted peers.

Bipedal locomotion requires an ultimate integration of dynamic postural control and propulsive force generation (Assaiante, 1998). In line with the results from the study of Houwen and co-workers, development of independent walking might be more challenging for children with a visual impairment than for their normally sighted peers. Insight into the age-related changes in the walking pattern of children with a visual impairment is highly important for the understanding of possible differences in gait maturation occurring without vision and could lead to the development of adequate rehabilitation programs. A functional and adaptive gait pattern highly contributes to independence and therefore has a large impact on the quality of life.

Some information on the gait pattern of adults with a visual impairment is available. Nakamura (1997) compared step-time parameters of gait in normally sighted, late blind and blind from birth individuals. Blind individuals had a slower walking speed, a shorter stride length and a prolonged duration of stance. He assumed that these adaptations reflected a strategy to maintain a more stable posture in the absence of vision. To our knowledge, no studies are performed on the development of gait in children with a visual impairment.

Therefore, the goal of the present study is to describe the age-related changes in gait in individuals with low vision and blindness. Spatial and temporal parameters of gait (STP) were determined as the general outcome parameters of the movement pattern characterizing performance. Data will be compared to an age-related control group.

2. Methods

2.1. Study design

A cross-sectional cohort study comparing a group of individuals with blindness, a group of individuals with low vision and a control group with normal vision was performed. The study was approved by the ethical committee of the University of Antwerp (UA A06 02).

2.2. Participants

Thirty-one individuals (15 females, 16 males) with a visual impairment, age range 1 year 3 months to 44 years, and 60 individuals (30 females, 30 males) with normal vision, age range 3 years 2 months to 46 years, participated in this study. Informed consent was obtained from the participant prior to testing. For the children, parents or legal guardians provided their consent.

Anthropometric information regarding the participants and information on the visual impairment can be found in Tables 1 and 2. All individuals with a visual impairment showed congenital disorders of the peripheral visual system. In the context of understanding developmental processes this group of visual disorders is the most informative since they have the lowest potential for confounding variables (Sonksen & Dale, 2002). Central processing of (visual) information is not affected in this population thus we are fairly certain that observed differences in STP of gait can only be related to the absence of visual information. Matching between the groups (visually impaired and controls) in age, mass and height was tested using the Kruskall–Wallis test and no significant differences were found.

Table 1

<table>
<thead>
<tr>
<th>Population with normal vision</th>
<th>Population with a visual impairment</th>
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<tbody>
<tr>
<td>Adults</td>
<td>Children</td>
</tr>
<tr>
<td>Adults</td>
<td>Children</td>
</tr>
<tr>
<td>n</td>
<td>20</td>
</tr>
<tr>
<td>Blind</td>
<td>4</td>
</tr>
<tr>
<td>Low vision</td>
<td>6</td>
</tr>
<tr>
<td>Age</td>
<td>18–45 years</td>
</tr>
<tr>
<td>Gender</td>
<td>9 men/11 women</td>
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<tr>
<td>Height</td>
<td>1.74 ± 0.07 m</td>
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<tr>
<td>Weight</td>
<td>68.0 ± 8.8 kg</td>
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Individuals with a visual impairment were referred to the study by the treating ophthalmologist who also provided information on visual acuity and visual field. Visual acuity (VA) testing was with Snellen optotypes and best binocular corrected vision was recorded. Visual field was tested with Goldman perimeter and V4 isopter. The visual handicap had to be present from birth and fall within the definition of visual impairment of the International Classification of Diseases (10th revision) that includes both low vision (1/20 ≤ VA ≤ 3/10 or visual field ≤ 20° in the better eye with best possible correction) and blindness (VA < 1/20 or visual field ≤ 10° in the better eye with best possible correction). Five children and four adults were completely blind (no light perception). All children showed normal intelligence levels, as shown by their scores on developmental testing available from their medical records. Exclusion criteria for participation were the presence of injuries to the lower extremities over the past six months and any neurological or orthopedic conditions.

2.3. Setting

Participants walked barefoot over an instrumented walkway (1.5 m × 9 m), free of obstacles, at preferred walking speed. Individuals with normal vision were instructed to look straight ahead. For individuals with a visual impairment, an intermittent auditory stimulus (speech) for orientation was provided at the end of the walkway. The first five walking trials were not included in the analysis to allow the participants to become familiar with the experimental set-up and surroundings. The next three walking trials were used for analysis.

Gait was recorded using an automated infrared camera system (Mcam 60, 6 cameras, 120 Hz, measurement error ±1.025 mm; Vicon, Oxford, UK). Markers were placed over the acromion, jugular notch of the sternum, xiphoid process of the sternum, C7, T10, spina iliaca anterior superior, sacral marker (midway between the posterior superior iliacal spines), thigh wand marker, lateral femoral epicondyles, tibial wand marker, lateral malleoli, calcanei and 2nd metatarsal heads according to the Plug-In-Gait™ marker set-up (Kadaba, Ramakrishnan, & Wootten, 1990).

2.4. Variables of interest and measurement

Walking speed was obtained from the forward displacement of the ankle marker (according to the Vicon Plug-in-Gait model). To compare between subjects of different size, walking speed was scaled to leg length by calculating the dimensionless walking speed (walking speed/√g × leg length with g = 9.81 m s⁻²) according to Hof (1996).

The heading angle is the angle between the line of progression and the forward direction (global Y axis). It represents the deviation from a straight path. The line of progression is calculated from the sacral marker trajectory. A regression line is fitted to the x (medio-lateral) versus y (forward) coordinates of the sacral marker and the slope of this regression line is the heading angle.

Events of heel strike and toe-off were determined based on force recordings and ankle marker trajectories. From these events step frequency (s⁻¹), stride length (m), step width (m), stance phase duration (% of gait cycle duration) and duration of double stance (% of gait cycle duration) were calculated. To allow comparison between subjects of different sizes dimensionless step frequency (step frequency/√g × leg length with g = 9.81 m s⁻²), dimensionless stride length (stride length/leg length) and dimensionless step width (step width/leg length) were determined according to Hof (1996).

2.5. Statistical analysis

Statistical analysis was performed in SPSS version 16.0.1 for Windows. Data from the three trials per individual were averaged. A mixed model ANOVA was performed to test for differences between groups and effects of age. Three groups were defined: individuals with normal vision (controls, n = 60), individuals with low vision (low vision, n = 21) and totally blind individuals (blind, n = 10). Curve estimation analysis showed that the STP showed the best fit (largest R²) for a logarithmic relation with age. Thus the dimensionless STP were added to the model as dependents, predictors are log(age) and group

### Table 2

Peripheral visual impairments. A list of the causes of the visual impairment in the individuals included in the study. Only conditions affecting the peripheral visual system are included in the study.

<table>
<thead>
<tr>
<th>Condition</th>
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<tbody>
<tr>
<td>Achromatopsia</td>
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<tr>
<td>Aniridie</td>
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<tr>
<td>Congenital cataract</td>
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<tr>
<td>Congenital glaucoma</td>
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<tr>
<td>Cone-rod dystrophy</td>
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<tr>
<td>Microphthalmia</td>
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<tr>
<td>Leber’s amaurosis</td>
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<tr>
<td>Ocular albinism</td>
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<tr>
<td>Optic aplasia</td>
</tr>
<tr>
<td>Toxoplasma infection in utero</td>
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<tr>
<td>Retinopathy of the premature</td>
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<tr>
<td>Retinitis pigmentosa</td>
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<tr>
<td>Retinal dystrophia</td>
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controls, low vision or blind). Both main effects and interaction effects are investigated. The significance level was set at $p < .05$. When there was a significant effect of group, post-hoc comparisons between the control, low vision and blind group were performed by multiple 2 sample $t$-tests. A Bonferroni correction for multiple comparisons was performed by adjusting the significance level to $p < 0.017$.

3. Results

Mean and standard deviation of the different STP per group can be found in Table 3. The relations with log(age) are shown in Fig. 1.

No overall differences are observed in mean heading angle ($p = .856$), dimensionless step frequency ($p = .342$) or mean dimensionless step width ($p = .515$) between the groups. Differences are observed in dimensionless walking speed ($p = 0.002$), dimensionless stride length ($p < 0.001$), stance phase duration ($p < 0.001$) and duration of the double support phase ($p < .001$). Post hoc comparisons revealed that blind individuals walk with a slower speed ($p < 0.001$), shorter stride length ($p < 0.001$) and prolonged duration of stance ($p < 0.001$) compared to both controls and the low vision group. Minor differences are observed between controls and the low vision group in dimensionless stride length ($p = 0.010$). Duration of double support is prolonged, both in blind ($p < 0.001$) and low vision ($p = 0.006$) compared to controls.

Dimensionless step frequency ($R^2 = 0.683$), dimensionless step width ($R^2 = 0.466$) and stance phase duration ($R^2 = 0.474$) show a significant relationship with log(age), representing the maturation of gait (Fig. 1). For double stance phase duration a significant interaction effect ($p = 0.017$) is observed between group and log(age). Fig. 1 shows that initially, double stance phase duration is much larger in the visually impaired group compared to the control group. However, it decreases rapidly with increasing age. Consequently the differences between both groups tend to disappear with increasing age.

Table 3
Step-time parameters of gait. Mean (SD) of the different spatial and temporal parameters are represented for each group.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Control group</th>
<th>Low vision group</th>
<th>Blind group</th>
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<tbody>
<tr>
<td>Dimensionless walking speed</td>
<td>0.456 (0.067)</td>
<td>0.422 (0.119)</td>
<td>0.262 (0.118)</td>
</tr>
<tr>
<td>Heading angle (°)</td>
<td>1.47 (1.04)</td>
<td>2.28 (2.17)</td>
<td>3.21 (3.51)</td>
</tr>
<tr>
<td>Stance phase duration (%)</td>
<td>59.61 (2.18)</td>
<td>62.84 (4.01)</td>
<td>56.89 (14.55)</td>
</tr>
<tr>
<td>Double support phase (%)</td>
<td>18.82 (3.94)</td>
<td>24.90 (8.03)</td>
<td>28.99 (18.75)</td>
</tr>
<tr>
<td>Dimensionless stride length</td>
<td>1.572 (0.159)</td>
<td>1.425 (0.258)</td>
<td>1.014 (0.331)</td>
</tr>
<tr>
<td>Dimensionless step frequency</td>
<td>0.843 (0.207)</td>
<td>0.892 (0.284)</td>
<td>1.001 (0.448)</td>
</tr>
<tr>
<td>Dimensionless step width</td>
<td>0.182 (0.057)</td>
<td>0.217 (0.084)</td>
<td>0.258 (0.151)</td>
</tr>
</tbody>
</table>

Fig. 1. Relations with log(age). The linear regressions of the step-time parameters that show a significant relation with log(age) are shown. If no statistically significant differences were found between groups, the regression line was fitted at the total. In case the groups differed significantly, a regression line was fitted at the subgroups. Circles (○) = controls, squares (□) = low vision, triangles (△) = blind.
4. Discussion

Our results represent overall improvements in motor performance with increasing age, in individuals with normal vision, low vision or blindness. However, differences were observed between groups in the spatial parameters of gait, as well as in timing of the different phases of the gait cycle. Especially totally blind individuals show adaptations in their gait pattern.

Limitations of the study are the small sample size \((n = 31)\) and the fact that only outcome parameters of gait were taken into account. We choose to focus on individuals with congenital disorders of the peripheral visual system. As motivated by Sonksen and Dale (2002), these children have the lowest potential for confounding variables, which improves the validity of the test results. However, children with this condition are rare. Sonksen and Dale (2002) report on an incidence of 350, born annually in the UK. In Europe, the prevalence of children with a visual handicap without associated handicaps is 0.1–0.41 per 1000 children. This motivates the small sample size.

Only outcome parameters of gait were taken into account since the primary goal of this study was to investigate age related changes in locomotion performances. As such, changes can be reported but only speculations can be made regarding the underlying causes of observed improvements in motor performance. Studies that also take into account the aspects of movement coordination and motor control need to be performed as well to support the formulated hypothesis.

As we included individuals with a visual impairment resulting from a range of pathologies, it may be possible to generalize our observations to most individuals with a visual impairment that results from congenital disorders of the peripheral visual system. Our results show that the individuals with low vision in our study perform rather well and show similar trends in motor skill performance as their normally sighted peers. Only when vision is completely absent are, important adaptations in the gait pattern observed. These results might be highly relevant for rehabilitation purposes. Poor locomotion performance in a child with a moderate visual impairment resulting from damage to the peripheral visual system might be alarming and require further investigation or follow-up. However, an important remark needs to be made. Gait was analyzed in a standard laboratory setting. It might very well be that a real life situation is much more challenging for children with a visual handicap and differences in performance of gait are revealed. In future studies it would be interesting to provide more challenging real-life situations when looking at gait performance.

As mentioned above, individuals with congenital disorders of the peripheral visual system who do not show orthopaedic or neurological conditions show a similar trend in motor skill (gait) development as their peers with normal vision. Locomotion skill development is characterized by a non-linear relationship with age, as previously reported in literature (Adolph, Vereijken, & Shroot, 2003). With increasing age, a decrease is observed in dimensionless step frequency, dimensionless step width and duration of stance. The trends observed in our population are similar to trends that can be identified using literature data (Hallemans, De Clercq, Otten, & Aerts, 2005; Kimura et al., 2005; Stolze et al., 1997; Sutherland, 1997).

Although individuals with a visual impairment perform rather well during overground locomotion a prolonged duration of the double support phase is observed, i.e. more time is spent with their two feet firmly on the ground and smaller steps are taken leading to a slower walking speed. In individuals showing blindness, alterations in gait pattern are more pronounced than in those with low vision.

Two alternative explanations can be formulated regarding the impact of visual deprivation on gait. A prolonged duration of the double support phase is generally considered as an indication of balance problems. Walking can be considered as a sequence of controlled falls. Double support, the period of the gait cycle during which both feet contact the ground, is a period of recovery of balance. In populations with poor balance, such as toddlers (Hallemans et al., 2005; Sutherland, 1997), elderly, and stroke patients more time is needed to recover the downward acceleration of the body. An increased duration of double support might indicate that children with a visual impairment are also confronted with balance problems.

Alternatively a prolonged duration of stance (and inherently also of double stance) allows for more time to use the foot to probe the ground (sensory feedback compensating for the loss of vision). This hypothesis of haptic exploration using the foot’s plantar surface to probe the ground was first formulated by Patla, Davies, and Niechwiej (2004). It was also supported by Buckley, MacLellan, Tucker, Scally, and Bennett (2008), who studied the visual guidance of landing behavior when stepping down to a new level. They found evidence that participants tended to probe the ground with their lead limb under modified visual conditions. Evidence consisted of the observation of a more backward position of the centre of mass whereby more weight is placed on the trail limb, a prolonged weight transfer time, a prolonged duration of trail limb support and modifications in knee, ankle and foot kinematics. Similar adaptations in gait are observed during overground locomotion in children and adults with normal vision that are blindfolded and in young adults with congenital disorders of the peripheral visual system (Hallemans et al., 2009a, 2009b; Hallemans et al., 2010). Both hypotheses are non-exclusive.

To confirm or reject one or both of our hypotheses further analysis is necessary. Measures of dynamical equilibrium providing information on the mechanisms of postural control can shed more light on the first hypothesis. Detailed kinematic analysis of the lead limb and information on foot unrolling can provide more information on the possible use of the foot as a probe.

5. Conclusion

In conclusion, individuals with congenital disorders of the peripheral visual system perform rather well during overground locomotion. Regarding age-effects, similar maturation trends are observed in STP of gait for individuals with
normal vision, low vision and blindness. However, adaptations in gait pattern are observed such as a shorter stride length and a prolonged duration of the double support phase. Gait adaptations are more pronounced in individuals with blindness than in those with low vision. The differences in gait pattern might be attributed to balance problems or could reflect a strategy to use the foot as a probe to provide additional haptic feedback information about the ground to compensate for loss of vision. Both hypotheses are non-exclusive.

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References


