



Collision avoidance strategies between two athlete walkers: Understanding impaired avoidance behaviours in athletes with a previous concussion

Natalie Snyder, Michael Cinelli, Victoria Rapos, Armel Crétual, Anne-Hélène
Olivier

► To cite this version:

Natalie Snyder, Michael Cinelli, Victoria Rapos, Armel Crétual, Anne-Hélène Olivier. Collision avoidance strategies between two athlete walkers: Understanding impaired avoidance behaviours in athletes with a previous concussion. *Gait & Posture*, 2022, 92, pp.24-29. <10.1016/j.gaitpost.2021.11.003>. <hal-03477399>

HAL Id: hal-03477399

<https://hal.science/hal-03477399v1>

Submitted on 13 Dec 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Collision avoidance strategies between two athlete walkers: understanding impaired avoidance behaviours in athletes with a previous concussion

Natalie Snyder^a, Michael Cinelli^a, Victoria Rapos^a, Armel Crétual^b, Anne-Hélène Olivier^b

^aDepartment of Kinesiology and Physical Education, Wilfrid Laurier University, Waterloo, ON, Canada

^bUniv Rennes, Inria, CNRS, IRISA, M2S, France

This work was supported by:

Natural Sciences and Engineering Research Council of Canada (NSERC; 2019-05894)

Mitacs Globalink Research Award Abroad- Campus France

BEAR Inria Associate team

Please address correspondence to

Michael E. Cinelli, PhD
Department of Kinesiology and Physical Education
Wilfrid Laurier University
75 University Ave, W. Rm. 501
Waterloo, ON, CA
mcinelli@wlu.ca

Natalie Snyder^a, Michael Cinelli^a, Victoria Rapos^a, Armel Crétual^b, Anne-Hélène Olivier^b

^aDepartment of Kinesiology and Physical Education, Wilfrid Laurier University, Waterloo, ON, Canada

^bUniv Rennes, Inria, CNRS, IRISA, M2S, France

This work was supported by:

Natural Sciences and Engineering Research Council of Canada (NSERC; 2019-05894)

Mitacs Globalink Research Award Abroad- Campus France

BEAR Inria Associate team

Please address correspondence to

Michael E. Cinelli, PhD
Department of Kinesiology and Physical Education
Wilfrid Laurier University
75 University Ave, W. Rm. 501
Waterloo, ON, CA
mcinelli@wlu.ca

Abstract:

Background: Individuals who have sustained a concussion often display associated balance control deficits and visuomotor impairments despite being cleared by a physician to return to sport. Such visuomotor impairments can be highlighted in collision avoidance tasks that involves a mutual adaptation between two walkers. However, studies have yet to challenged athletes with a previous concussion during an everyday collision avoidance task, following return to sport.

Research Question: Do athletes with a previous concussion display associated behavioural changes during a 90°-collision avoidance task with an approaching pedestrian?

Methods: Thirteen athletes (ATH; 9 females, 23±4years) and 13 athletes with a previous concussion (CONC; 9 females, 22±3 years, concussion <6 months) walked at a comfortable walking speed along a 12.6m pathway while avoiding another athlete on a 90°-collision course. Each participant randomly interacted with individuals from the same group 20 times and interacted with individuals from the opposite group 21 times. Minimum predicted distance (*mpd*) was used to examine collision avoidance behaviours between ATH and CONC groups.

Results: The overall progression of *mpd*(t) did not differ between groups ($p>.05$). During the collision avoidance task, previously concussed athletes contributed less when passing second compared to their peers($p<.001$). When two previously concussed athletes were on a collision course, there was a greater amount of variability resulting in inappropriate adaptive behaviours.

Significance: Although successful at avoiding a collision with an approaching athlete, previously concussed athletes exhibit behavioural changes manifesting in riskier behaviours. The current findings suggest that previously concussed athletes possess behavioural changes even after being cleared to returned to sport, which may increase their risk of a subsequent injury when playing.

Keywords: mutual adaptation; adaptive locomotion; visuomotor integration; person-person interactions; concussion; contact sport

1. Introduction

It is estimated that 3.8 million Sports Related Concussions (SRC) occur in the United States per year with almost 50% of SRC going unreported[1]. SRC are a traumatic brain injury caused by biomechanical factors, resulting from a direct blow to the head, face, or neck causing short-lived neurological impairments[2]. SRC vary in severity and clinical symptoms ranging from headaches and nausea to severe neurological impairments[2]. Research involving athletes who have sustained a SRC, have identified associated balance control deficits and highly variable actions when performing visuomotor processing tasks, such as dual tasks or perception-

action coupling tasks, persisting well beyond the identified recovery period and return to sport [3-15]. Thus, physical symptom recovery post-SRC may not be indicative of absolute recovery leading to an increased likelihood of sustaining another concussion or injury during an everyday task [1,11,13,16], such as avoiding a collision with an object or approaching pedestrian.

Recent research has observed and quantified individual avoidance behaviours during a collision avoidance task involving two pedestrians approaching one another at a 90° angle [17-18]. The mutual avoidance between two pedestrians during a 90°-collision avoidance task can be described using the evolution of Minimum Predicted Distance (*mpd*), which predicts the future risk of collisions between two walkers [17-18]. In such a task, role-dependent strategies can be identified based on crossing order such that, the walker passing second contributes more to the avoidance situation compared to the walker passing first, regardless of age [18-19]. These role-dependent strategies are established at the initial sight of one another and are maintained throughout the entirety of the avoidance task such that, the walker who is intended to pass first at the beginning of the interaction (based on walkers' respective velocity and position) is the one who passes first at the time of crossing [18,21]. This 90°-collision avoidance task and *mpd* analyses has proved to be an effective paradigm to quantify avoidance behaviours (i.e., contribution to avoidance, role identification to the avoidance, and temporal evolution of an avoidance) across the lifespan, highlighting visuomotor changes due to development and aging [19-20].

Given the discrepancy in athlete recovery following a SRC, it is essential to examine avoidance behaviours in athletes with a previous concussion during an everyday collision avoidance situation, in which they must adapt their locomotor speed and path trajectory to avoid

another pedestrian. It is possible that these athletes are more susceptible to a subsequent injury or collision due to associated visuomotor changes.

Thus, the objective of the current study was to examine avoidance behaviours during a 90°-collision avoidance task with an approaching pedestrian in athletes with a previous concussion. It was hypothesized that athletes with a previous concussion would demonstrate differences in their collision avoidance behaviour due to associated visuomotor impairments. Specifically, by using a 90°-collision avoidance task with an approaching pedestrian and *mpd* analyses, athletes with a previous concussion were expected to have riskier collision avoidance strategies highlighted through changes in the temporal evolution of *mpd* as well as, difficulties identifying role-dependent strategies.

2. Materials and methods

2.1 Participants

Thirteen athletes with a previous concussion (CONC; 9 females, 22±3 years) and 13 non-concussed control athletes (ATH; 9 females, 23±4years) participated in the study (Table 1). All participants completed informed consent and a health history questionnaire to determine eligibility to participate (i.e., no known neurological/ movement disorders or injury impairing locomotion, and normal/corrected normal vision). All CONC completed the sport concussion assessment tool 5th edition (SCAT-5)[22] which provided information regarding time of injury and return to sport (Table 1). CONC were rugby players who had sustained an SRC within one year of participation, were asymptomatic during data collection, and had been cleared to return to sport by a physician. ATH played a contact sport such as rugby, football, or handball and had not sustained an SRC within the last 24 months of participation. The study was approved by the ethics boards at both universities.

2.2. *Experimental design*

Each experimental session was conducted in a 9mx9m area consisting of four occluding walls [cf. 17-18]. The occluding walls allowed participants to reach steady state locomotion prior to viewing the other individual involved in the avoidance task (Figure 1). Multiple participants of the same sex were recruited per experimental session, to explore natural behaviours and limit interaction biases. There were a total of six experimental sessions performed: five sessions consisting of 2 CONC and 2 ATH and one session consisting of 3 CONC and 3 ATH. Ideally, 3 participants per group for each experimental session would limit interaction biases however, due to difficulty recruiting CONC, most of the experimental sessions involved 2 participants per group. During each session, participants occupied one of the four corners of the experimental space and were unaware of who they were interacting with (i.e., CONC or ATH) on any given trial. Participants were outfitted with a helmet consisting of four 4mm reflective markers, representing a unique rigid body. Head position data were recorded using 24 Vicon cameras, positioned above the experimental area, at a sampling frequency of 120Hz.

2.3. *Protocol*

Trials consisted of two participants, not sharing the same diagonal, walking to their opposite corner of the experimental area. Participants were instructed to walk at a comfortable pace to the opposite corner without colliding with another individual. An audible monotone “GO” signal was provided by the experimenter to notify participants to begin the trial. Trials were randomized and included the following interactions: 1) two ATH, 2) one ATH and one CONC, 3) two CONC, and 4) individual walking trials. Each participant interacted with individuals from the same group an equal number of times as interacting with individuals from the opposite group. A total of 92 trials were completed in experimental sessions involving 2

CONC and 2 ATH and a total of 141 trials were completed in the experimental session involving 3 CONC and 3 ATH. Trials were separated into blocks to change the configuration of participants in each corner to limit interaction biases and to ensure all combinations of interactions could be completed.

2.3 Data analysis

Participant's movement was computed as a single point placed in the centre of the helmet and was used to determine *mpd* and the contribution to collision avoidance. Data reconstruction of the positional data were smoothed using a 0.5Hz low pass 2nd order Butterworth filter, removing high stepping oscillations. Velocity was computed using the time derivative of each participant's location.

Trials were separated into the following four groups based on the participants involved and who crossed first: 1) ATH-ATH; 2) CONC-CONC; 3) CONC-ATH; and 4) ATH-CONC. We computed *mpd* at each instant of time (t) for each collision avoidance trial [cf. 17]. This resulted in $mpd(t)$ representing the theoretical crossing distance between participants' future position based on a linear extrapolation of their trajectory given their current position and speed at time(t) [16]. Any variation of $mpd(t)$ indicates that a motion adaptation to avoid a collision occurred between two walkers. Specifically, we were interested in the interaction period between the two walkers, which ranged from the time individuals first saw one another past the occluding walls (t_{see}) to the time of crossing (t_{cross} , i.e., the clearance distance). As a result, a temporal normalization of the interaction period from t_{see} (i.e., 0% of the interaction) to t_{cross} (i.e., 100% of the interaction) was conducted for each trial to enable comparisons of *mpd* time series between groups.

Moreover, $mpd(t)$ was assigned according to the final crossing order between two walkers in such a way that allowed for a positive $mpd(tcross)$. In doing so, a positive $mpd(tsee)$ suggests that crossing order was preserved along the entire interaction. Alternatively, a negative $mpd(tsee)$ is the result of an inversion in crossing order between the two walkers such that, walker #1 was intended to pass first based on linear extrapolation however walker #2 ended up passing first at $tcross$. Thus, the number of inversions in crossing order was computed and was separated for all subsequent analyses as we are unable to examine the temporal evolution of mpd in such trials.

To examine collision avoidance behaviours, only trials where a motion adaptation occurred were considered. Motion adaptations to avoid collisions resulted in increases in mpd during the interaction period, such that $mpd(tcross) > mpd(tsee)$. Thresholds for motion adaptation were identified by dividing the data into trials where: 1) $mpd(tcross) > mpd(tsee)$ ($mpdCA$); and 2) $mpd(tcross) \approx mpd(tsee)$ (i.e., no motion adaptation was performed) [cf. 22]. A threshold was determined for each group using the equation:

$$f(x) = \begin{cases} a \times x + b & \text{if } x < mpdCA, \text{ with } b = (1 - a) \times mpdCA \\ x, & \text{otherwise} \end{cases} \quad (1)$$

where a and $mpdCA$ minimized the sum of squared residuals between the data and the model. By fitting a piecewise linear function onto the evolution of $mpd(tcross)$ with respect to $mpd(tsee)$, the switch point between the two pieces is identified as the threshold for motion adaptation.

The cumulative contribution (m) along the interaction period of the walker passing first and the walker passing second were computed using partial derivatives of $mpd(t)$ [18]. Only trials where a motion adaptation with a minimum change of 0.05m between $mpd(tsee)$ and

$mpd(tcross)$ was considered. Anything less than 0.05m would be too small of a change for an individual to change their behaviour.

2.4 Statistics

GLM were conducted for each variable to explore group differences, (α set to 0.05). Normality and homogeneity of variance were assessed using Shapiro-Wilk and Levene tests. Average walking speed for ATH and CONC groups were compared using Welch's t-test. A Pearson's chi-square was conducted for each group interactions to examine the number of inversions to $mpd(t)$. The effect of group interaction on clearance distance ($mpd(tcross)$) for all trials with a motion adaptation were assessed using a One-way ANOVA and post-hoc analysis. Statistical Parametric Mapping (SPM)[24] and post-hoc analysis were conducted to compare the difference in the evolution of $mpd(t)$ between groups from $tsee$ to $tcross$. Bonferroni corrections were applied to all p-values with the level of significance remaining at $\alpha=0.05$. Last, paired samples t-tests using SPM were completed for each group to explore contribution to avoid a collision between participants.

3. Results

3.1 Walking speed

No collisions occurred throughout any of the experimental sessions between participants. Average walking speed during the individual catch trials were analyzed. CONC walked significantly slower ($1.41 \pm 0.13\text{m/s}$) compared ATH ($1.46 \pm 0.08\text{m/s}$) ($t(63.42)=2.3, p=.02, d=.52$).

3.2 Inversion of crossing order

Of the total trials reconstructed, there were several trials involving a negative $mpd(tsee)$, meaning an inversion in crossing order occurred. There were a greater number of inversions in

crossing order during CONC-ATH trials (22.9%) (i.e., CONC was expected to pass first) compared to any other groups ($\chi^2(3)=7.86, p=.049$; Table 2).

3.3 Threshold for motion adaptation (maximum distance)

Considering trials when an inversion in crossing order did not occur (i.e., $mpd(t_{see}) > 0$), the threshold to trigger an adaptation differed between groups (Table 2), the smallest threshold occurring during CONC-CONC trials (0.84m). This threshold of 0.84m was used for subsequent $mpd(t)$ analyses.

3.4. Minimum Predicted Distance (mpd)

The average $mpd(t)$ for all four group interactions, when $mpd(t_{see}) < 0.84m$ and for all positive $mpd(t_{see})$ were analysed using SPM (Figure 2). Analyses only revealed a significant effect of group interactions on $mpd(t)$ at the beginning of the interaction period, from 0% to 3% of the interaction ($F^* > 3.65, p=.045$). During this initial interaction, post-hoc analysis revealed a significant difference between ATH-ATH and CONC-CONC groupings ($p=.008$). The remainder of the interaction period and overall progression of $mpd(t)$ for all group interactions were not significantly different from one another ($p > .05$). As well, there were no differences between clearance distance ($mpd(t_{cross})$) between the four groups ($F(3,441)=1.17, p=.32, f=.008$; Table 2).

3.5. Contribution to collision avoidance (t_{see} to t_{cross})

During the interaction period, a cumulative contribution must occur from both walkers to avoid a collision. SPM paired t-test analyses revealed significant differences between the contribution to collision avoidance based on who was interacting with one another and their designated roles, the walker passing first or the walker passing second (Figure 3). In the ATH-ATH interactions, the contribution to collision avoidance of the individual passing second is greater than the contribution of the individual passing first during the majority of the interaction

(i.e., 5%-100% of the interaction, $t > 2.89, p < .001$; Figure 3a). Comparatively, in the CONC-CONC interactions the contribution of the individual passing second is greater than the contribution of the individual passing first from 57%-100% of the interaction, with a greater amount of variability ($t > 2.95, p < .001$; Figure 3d). In the CONC-ATH grouping, the contribution of the ATH is greater than the contribution of the CONC from 40% to 100% of the interaction ($t > 2.93, p < .001$; Figure 3b). Last, in the ATH-CONC grouping there were no significant differences between walkers' contribution to collision avoidance, apart from one marginal difference at the beginning of the interaction (0%-4%), where the contribution of the ATH was larger than the CONC ($t > 2.90, p < .045$; Figure 3c).

4. Discussion

The study aimed at evaluating whether previously concussed athletes (CONC) demonstrated visuomotor processing impairments manifesting as differences in avoidance behaviours during a 90°-collision avoidance task with an approaching walker. Our results revealed that CONC exhibit behavioural changes, persisting beyond physician clearance to return to sport, including improper contribution to collision avoidance and difficulty identifying role-dependent strategies during an everyday collision avoidance task with an approaching walker.

Minimum Predicted Distance (*mpd*), was analyzed as a function of time throughout the interaction period to examine contribution to collision avoidance between athletes. Comparing initial response to collision avoidance, the threshold for motion adaptation between two control athletes (ATH-ATH) was similar to previous findings in young adults (~1m)[17-20]. However, when two CONC interacted (CONC-CONC), riskier collision avoidance strategies manifested in a smaller adaptation threshold (0.84m). In fact, motion adaptation thresholds were smaller for CONC-CONC interactions compared to when at least one ATH was involved (Table 2). The

smaller motion threshold suggests CONC were more likely to collide or pass relatively closer to one another if no adaptation to speed or trajectory occurred. Likewise, a smaller threshold may imply that CONC have associated deficiencies with perception action-boundaries resulting in riskier collision avoidance strategies[13]. However, this initial risk of a collision was not maintained throughout the interaction with the other pedestrian. The overall progression of $mpd(t)$ and the clearance distance were similar between ATH and CONC groups(Figure 2). A similar clearance distance between groups emphasizes the preservation of anticipatory locomotor adjustments in CONC following their clearance to return to play. Thus, the similar clearance distance between ATH and CONC groups suggests latter understand their action boundaries as the potential of a collision gets closer. However, CONC may require a greater amount of time to process an impending collision and make adjustments due to visuomotor deficiencies, as evidenced by a slower walking speed compared to the control athletes and a smaller motion adaptation at initial sight of an approaching pedestrian(tsee; Table 2).

Despite a similar $mpd(t)$ (in trials with no inversions), there is evidence of associated visuomotor deficits in CONC. First, there were a greater number of inversions in crossing order when CONC were expected to pass first (CONC-ATH, Table 2). Typically, passing second or slowing down can be considered a cautious strategy as it allows for an individual to attend and maintain view the walker passing first[25]. However, in the case of a mutual avoidance, an inversion in crossing order results in improper avoidance strategies and an increased risk of a collision due to an impairment in perception-action processing. Specifically, CONC may have perceived the collision appropriately however, it took longer for them to process the information and produce an appropriate response resulting in improper collision avoidance strategies[3], such

as slowing down rather than speeding up to ensure a collision did not occur with the walker who was intended to pass second.

Likewise, the contribution to collision avoidance differed between ATH and CONC groups based on crossing order and who was interacting. Similar to previous studies with young adults, two control athletes interacting were able to establish role-dependent strategies such that, the individual passing second contributed more to the collision avoidance (Figure 3a) [17-20]. However, when CONC were involved in the interaction, they contributed less to the mutual collision avoidance behaviour when identified as passing second (ATH-CONC; Figure c). In other words, ATH quickly adapted to prevent the collision with CONC by contributing more to the collision avoidance. Thus, ATH adapted their trajectory to ensure successful clearance even when passing first. Improper contribution to collision avoidance is further emphasized during CONC-CONC interactions, the relative contribution to collision avoidance is highly variable and is associated with improper adaptation strategies (Figure 3d). In other words, when two CONC are on a collision course, there is a discrepancy in establishing role dependent strategies to collision avoidance, resulting in decreasing *mpd* (i.e., as depicted by the negative variability) rather than increasing the distance between them. This is consistent with previous research suggesting that individuals who have sustained a previous concussion exhibit highly variable actions during visuomotor tasks [3,5,9,11-12]. In summary, the differences in contribution to collision avoidance, crossing order, and high variability suggest CONC have impairments in visuomotor processing, resulting in improper collision avoidance strategies, even after being cleared to return to sport.

It is important to note that ATH and CONC did have an overall smaller clearance distance compared to previous literature with young adults. Smaller clearance distances may be

due to athletic training, however adaptations to $mpd(t)$ were consistent between control athletes and previous collision avoidance literature[17-20]. Additionally, all interactions compared avoidance behaviours of athletes of the same sex and similar size, therefore collision avoidance behaviours are not based on physical characteristics[21], rather based on perceptions of the other pedestrian's movements. Possibility of biases in avoidance behaviours based on athletes knowing one another and their concussion history prior to completing the study were mitigated through the use of multiple trials, recruiting multiple participants per session, and the room set up (i.e., 90° walking trajectories, having walls preventing any prior knowledge as to who participants were interacting with until they were at steady-state locomotion, and little time to react).

Conclusion

Previously concussed athletes displayed ineffective behavioural changes during an everyday collision avoidance task, which may be due to residual visuomotor impairments. The riskier behaviour displayed throughout the collision avoidance task may be associated with biomechanical changes[11] or perception-action processing difficulties[13] following a concussion, thus increasing the likelihood of sustaining a subsequent injury following a concussion once they have returned to play. The results from the current study should be used as a basis for future studies to investigate biomechanical constraints, perceptual judgements, reaction time, and visuomotor processing in athletes with a previous concussion who have been cleared to return to play. As well, further analysis is needed to understand these associated changes in behaviours, specifically in a sports-related collision avoidance interactions using virtual reality protocols.

Conflict of Interest: There were no conflicts of interest.

	Athletes with a previous concussion (N=13)				Athletes (N=13)			
	Average	Standard Deviation	Max	Min	Average	Standard Deviation	Max	Min
Age (years)	22	± 2.9	27	18	23	± 3.7	31	19
Sex	9 Females	-	-	-	9 Females	-	-	-
SCAT5 Symptom Score	8	± 15	56	0	4	± 6	23	0
No. of Symptoms	4	± 5	17	0	3	± 4	12	0

Table 1: Characteristics of athletes with a previous concussion (CONC) and athletes (ATH).

No. of Previous Concussion	2	± 1	3	1	<1	-	1	0
No. of days since Last Concussion	111	± 91	365	22	-	-	>730	-
No. of days to Clinical Recovery	25	± 21	90	7	-	-	>730	-

Table 2: Threshold for motion adaptations, inversions in crossing order, and the average clearance distance for each of the four group interactions, 1) athlete – athlete (ATH - ATH), 2) athlete - athlete with previous concussion (ATH – CONC), 3) athlete with previous concussion – athlete (CONC – ATH), and 4) athlete with previous concussion – athlete with previous concussion (CONC – CONC).

	1) ATH-ATH	2) ATH-CONC	3) CONC-ATH	4) CONC-CONC
Threshold for motion adaptation (m)	1.07	0.97	0.93	0.84
Inversion of crossing order (%)	14.7	10.4	22.9	14.8
Clearance distance (m)	0.74 \pm 0.15	0.71 \pm 0.14	0.72 \pm 0.14	0.71 \pm 0.14

Figure Captions

Figure 1: A) Experimental setup of the 90°-crossing experimental set-up consisting of four occluding walls within a 12m x 12m area. P1 and P2 represent 2 participants involved in one trial. P(start) refers to the position of participant when starting the trial, P(tsee) is the position of each participant when they are first able to see one another (i.e. when they are not anymore occluded by the walls), and P(tcross) is the position of each participant when they cross, at the distance of closest approach. B) Real world image of two athletes interacting within the experiment.

Figure 2: Mean positive $mpd(t)$ evolution over time for each group pairings between athlete (ATH) and athlete with previous concussion (CONC). Significant differences are represented by horizontal lines at the bottom of the figure ($p < .05$)

Figure 3: Contribution (mean and SD) to $mpd(t)$ between walker #1 and walker #2 between: A) athlete - athlete interactions (ATH-ATH), B) athlete with previous concussion - athlete interactions (CONC-ATH), C) athlete – athlete with previous concussion interactions (ATH-CONC), and D) athlete with previous concussion – athlete with previous concussion interactions (CONC-CONC). Significant differences during the interaction period between the walker passing first and the walker passing second are represented by horizontal lines at the bottom of each figure ($p < .001$).

References:

- [1] Harmon, K.G., Clugston, J.R., Dec,K., Hainline, B., Herring, S., Kane, S.F.,...Roberts, W.O. (2013). American medical society for sports medicine position statement: concussion in sport. *British Journal of Sports Medicine*. 47(1), 15-26. DOI: 10.1136/bjsports-2012-091941
- [2] McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S...Vos, P.E. (2016). Consensus statement on concussion in sport- the 5th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*, 51, 838-847. DOI: 10.1136/bjsports-2017-097699
- [3] Baker, C.S. & Cinelli, M.E. (2014). Visuomotor deficits during locomotion in previously concussed athletes 30 or more days following return to play. *Physiological Reports*. 2(12), e12252. DOI: 0.14814/phy2.12252
- [4] Caccese, J.B., Santos, F.V., Yamaguchi, F.K., Buckley, T.A., & Jeka, J.J. (2021). Persistent visual and vestibular impairments for postural control following concussion: A cross-sectional study in university students. *Sports Medicine*, 1-12. DOI: 10.1007/s40279-021-01472-3
- [5] Fait P., Swaine, B., Cantin, J-F., Leblond, J., & McFadyen, B.J. (2013). Altered integrated locomotor and cognitive function in elite athletes 30 days postconcussion: a preliminary study. *Journal of Head Trauma and Rehabilitation*, 28(4), 293-301. DOI: 10.1097/HTR.0b013e3182407ace
- [6] Locklin, J., Bunn, L., Rou., E., & Danckert, J. (2010). Measuring deficits in visually guided action post-concussion. *Sports Medicine*, 40(3), 183-187. DOI: 10.2165/11319440-000000000-00000.

- [7] Powers, K.C., Kalmar, J.M., & Cinelli, M.E. (2014). Recovery of static stability following a concussion. *Gait & Posture*, 39(1), 611-614. DOI: 10.1016/j.gaitpost.2013.05.026
- [8] Reilly, N., Prebor, J., Moxey, J., & Schussler, E. (2020). Chronic impairments of static postural stability associated with history of concussion. *Experimental Brain Research*, 238, 2783-2793. <https://doi.org/10.1007/s00221-020-05934-4>
- [9] Slobounov, S., Slobounov, E., & Newell, K. (2006). Application of virtual reality graphics in assessment of concussion. *CyberPsychology & Behavior*, 9(2), 188-191. <https://doi.org/10.1089/cpb.2006.9.188>
- [10] Wood, T.A., Hsieh, K.L., An, R., Ballard, R.A., & Sosnoff, J.J. (2019). Balance and gait alterations observed more than 2 weeks after concussion: A systematic review and meta-analysis. *American Journal of Physical Medicine & Rehabilitation*, 98(7), 566-576. DOI:10.1097/PHM.0000000000001152
- [11] Howell, D., Osternig, L., & Chou, L-S. (2015). Monitoring recovery of gait balance control following concussion using an accelerometer. *Journal of Biomechanics*, 12(18), 3364-3368. <https://doi.org/10.1016/j.jbiomech.2015.06.014>
- [12] Slobounov, S., Gay, M., Johnson, B., & Zhang, K. (2012). Concussion in athletics: ongoing clinical and brain imaging research controversies. *Brain Imaging and Behavior*, 6, 224-243. <https://doi.org/10.1007/s11682-012-9167-2>
- [13] Eagle, S.R., Nindl, B.C., Johnson, C.D., Kontos, A.P., & Connaboy, C. (2021). Does concussion affect perception-action coupling behavior? Action boundary perception as a biomarker for concussion. *Clinical Journal of Sport Medicine*, 31(3), 273-280. DOI: 10.1097/JSM.0000000000000731

- [14] Martini, D.N., Sabin, M.J., DePesa, S.A., Leal, E.W., Negrete, T.N., Sosnoff, J.J., & Broglio, S.P. (2011). The chronic effects of concussion on gait. *Archives of Physical Medicine and Rehabilitation*, 92(4), 585-589. DOI: 10.1016/j.apmr.2010.11.029
- [15] Kamins, J., Bigler, E., Covassin, T., Henry, L., Kemp, S., Leddy, J.L.,...& Giza, C.G. (2017). What is the physiological time to recovery after concussion? Systematic review. *Br J Sports Med*, 0, 1-7.
- [16] Chmielewski, T.L., Tatman, J., Suzuki, S., Horodyski, M., Reisman, D.S., Bauer, R.M., Clugston, J.R., & Herman, D.C. (2021). Impaired motor control after sport-related concussion could increase risk for musculoskeletal injury: Implications for clinical management and rehabilitation. *Journal of Sport and Health Science*, 10(2), 154-161. DOI: 10.1016/j.jshs.2020.11.005.
- [17] Olivier, A-H., Marin, A., Crétual, A., & Pettré, J. (2012). Minimal predicted distance: A common metric for collision avoidance during pairwise interactions between walkers. *Gait & Posture*, 36, 399-404. <https://doi.org/10.1016/j.gaitpost.2012.03.021>
- [18] Olivier, A-H., Marin, A., Crétual, A., Berthoz, A., & Pettré, J. (2013). Collision avoidance between two-walkers: Role-dependent strategies. *Gait & Posture*, 38, 721-756. <https://doi.org/10.1016/j.gaitpost.2013.03.017>
- [19] Rapos, V., Cinelli, M., Snyder, N., Crétual, A., & Olivier, A-H. (2019). Minimum Predicted Distance: applying a common metric to collision avoidance strategies between children and adult walkers. *Gait & Posture*, 72, 16-21. <https://doi.org/10.1016/j.gaitpost.2019.05.016>
- [20] Rapos, V., Cinelli, M., Grunberg, R., Bourgaize, S., Crétual, A., & Olivier, A-H. (2021). Collision avoidance behaviours between older adult and young adult walkers. *Gait &*

- Posture*. 88, 210-215. <https://doi.org/10.1016/j.gaitpost.2021.05.033>
- [21] Knorr, A.G., Willacker, L., Hermsdörfer, S., Glasauer, S., & Krüger, M. (2016). Influence of person- and situation-specific characteristics on collision avoidance behaviour in human locomotion. *Journal of Experimental Psychology: Human Perception and Performance*, 42(9), 1332-1343, <https://doi.org/10.1037/xhp0000223>
- [22] Echemendia, R. J., Meeuwisse, W., McCrory, P., Davis, G.A., Putukian, M., Leddy, J.,... Herring, S. (2017). The sport concussion assessment tool 5th edition (SCAT5): background and rationale. *British Journal of Sports Medicine*, 51(11), 848-850. <http://dx.doi.org/10.1136/bjsports-2017-097506>
- [23] Berton, F., Olivier, A., Bruneau, J., Hoyet, L., & Pettre, J. (2019). Studying Gaze Behaviour during Collision Avoidance with a Virtual Walker: Influence of the Virtual Reality Setup. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Osaka, Japan, 717-725 DOI: 10.1109/VR.2019.8798204.
- [24] Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., and Nichols, T. E. (2011). *Statistical Parametric Mapping: The Analysis of Functional Brain Images: The Analysis of Functional Brain Images*. Cambridge, MA: Academic press.
- [25] Croft, J.L., Panchuk, D. (2017). What where you're going? Interferer velocity and visual behavior predicts avoidance strategy during pedestrian encounter. *J. Motor Behav*, 1-11.

Figure-1

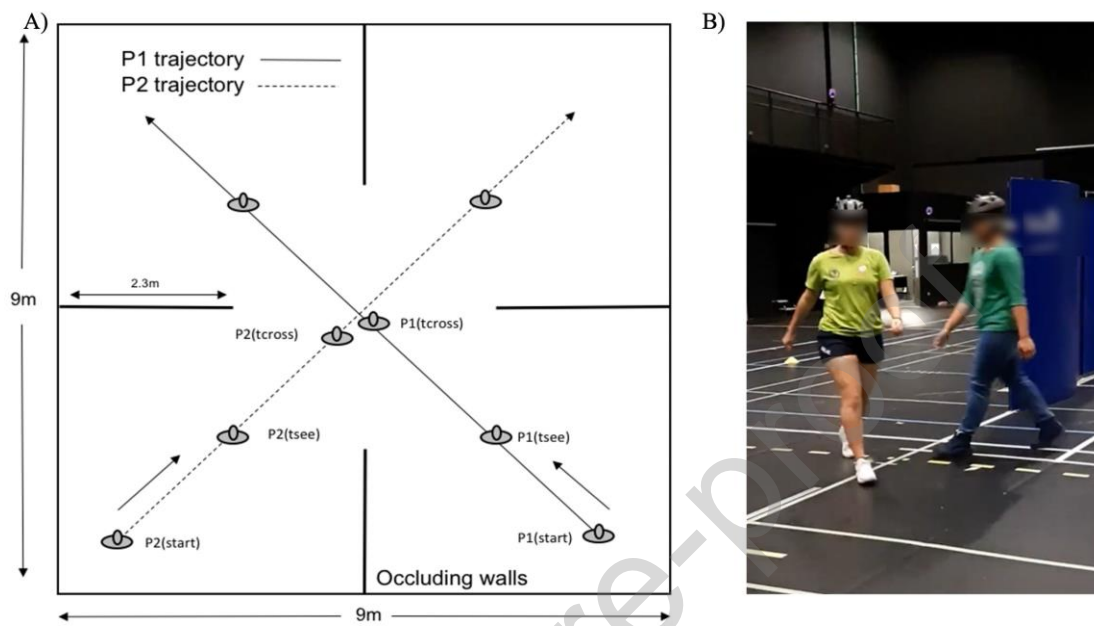
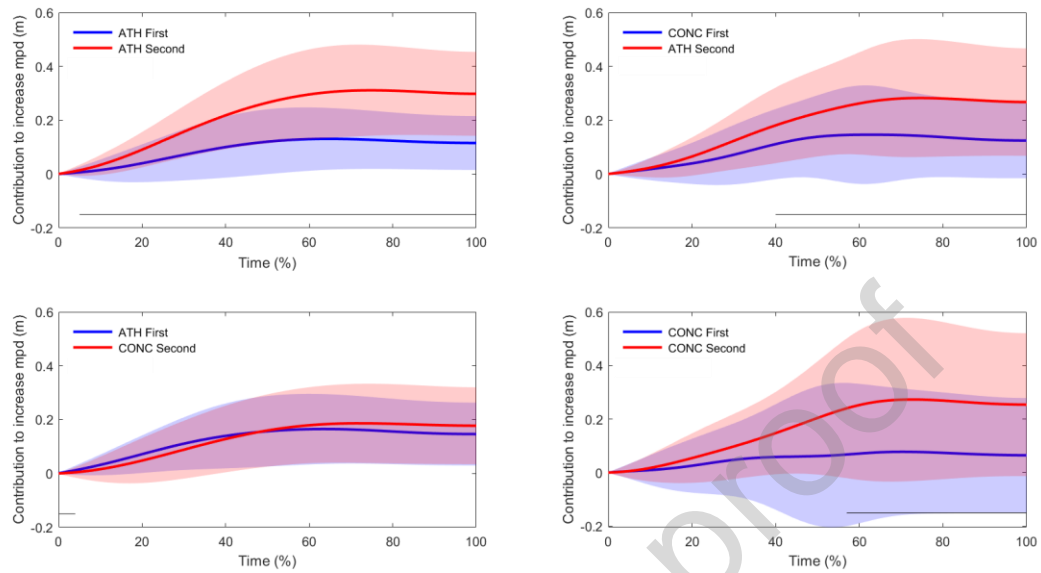
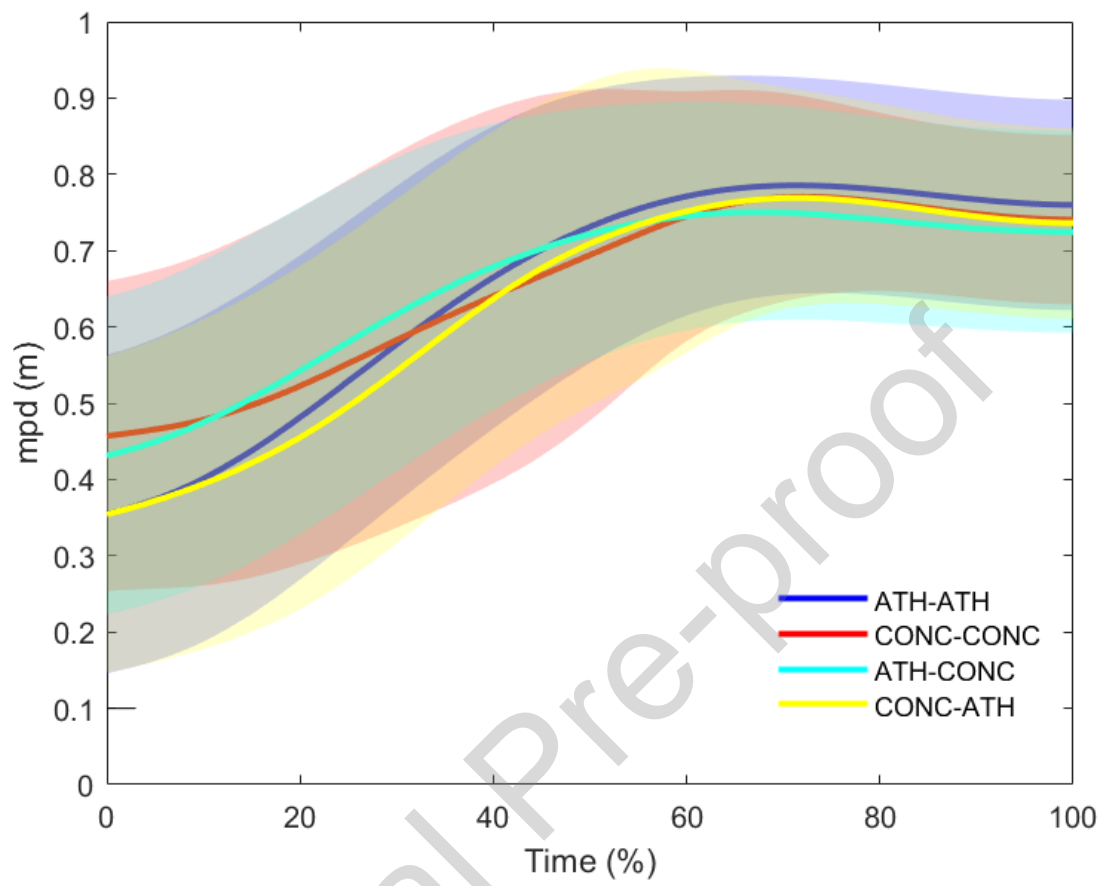


Figure-2





Highlights:

- Safe collision avoidance requires a mutual adaptation using visuomotor processing
- Previously concussed athletes contribute less to mutual avoidance of collisions
- Two previously concussed athletes on collision courses yield highly variable actions
- Previously concussed athletes possess behavioral changes beyond return to sport