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A new ball launching system with controlled flight parameters for catching experiments

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ABSTRACT

Systematic investigations of sensorimotor control of interceptive actions in naturalistic conditions, such as catching or hitting a ball moving in three-dimensional space, requires precise control of the projectile flight parameters and of the associated visual stimuli. Such control is challenging when air drag cannot be neglected because the mapping of launch parameters into flight parameters cannot be computed analytically. We designed, calibrated, and experimentally validated an actuated launching apparatus that can control the average spatial position and flight duration of a ball at a given distance from a fixed launch location. The apparatus was constructed by mounting a ball launching machine with adjustable delivery speed on an actuated structure capable of changing the spatial orientation of the launch axis while projecting balls through a hole in a screen hiding the apparatus. The calibration procedure relied on tracking the balls with a motion capture system and on approximating the mapping of launch parameters into flight parameters by means of polynomials functions. Polynomials were also used to estimate the variability of the flight parameters. The coefficients of these polynomials were obtained using the launch and flight parameters of 660 launches with 65 different initial conditions. The relative accuracy and precision of the apparatus were larger than 98% for flight times and larger than 96% for ball heights at a distance of 6 m from the screen. Such novel apparatus, by reliably and automatically controlling desired ball flight characteristics without neglecting air drag, allows for a systematic investigation of naturalistic interceptive tasks.

1. Introduction

The identification of which mechanisms underlie our use of visual information and prior knowledge of physical laws to guide interceptive actions is still an open question (Zago et al., 2009). Intercepting a moving object is a demanding task because visual stimuli guiding movement execution change in time and the central nervous system (CNS) must update on-line or predict the object position to compensate for sensorimotor latencies and bring the arm to the right place at the right time. To date, several experimental paradigms have been used to investigate the sensorimotor control mechanisms employed by the CNS to accomplish a variety of interceptive tasks. Motor responses have been characterized when capturing or punching an object moving along a linear path such as a ball dropped vertically with different motions (Lacquaniti et al., 1993; Lacquaniti and Maioli, 1989, 1987; Zago et al., 2005; Zago and Lacquaniti, 2005), when catching (Bennett et al., 1999) or striking (Tresilian and Lonergan, 2002; Tresilian and Plooy, 2006; Tresilian et al., 2009) a target moving along a horizontal linear track, when intercepting targets moving on a computer monitor (Brenner and Smeets, 2007; Brouwer et al., 2000, 2002a,b, 2003; Mrotek and Soechting, 2007) or on a head-mounted display (Senot et al., 2005), when intercepting a ball attached on a rod and dropped from the ceiling of the room (Dessing et al., 2009; Peper et al., 1994), and when catching, hitting or batting a ball thrown by a launching machine, both while standing still (Brouwer et al., 2002b; Button et al., 2002; Land and McLeod, 2000; Laurent et al., 1994; Mazyn et al., 2006, 2007; Montagne et al., 1999; Regan, 1997; Savelsbergh et al., 2002; Tijtgat et al., 2009) and while running to reach the ball (McBeath et al., 1995; McLeod and Dlenes, 1993; McLeod et al., 2001).

In particular, tasks requiring the interception of balls flying in three-dimensional space offer a powerful tool to investigate the motor control strategies exploited by humans to accomplish interceptive actions. Indeed, they require the correct interpretation of motion in depth (Regan et al., 1979; Regan and Beverley, 1978)

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and of the retinal expansion of the object image while approaching a subject (Lee, 1980). Motor responses are influenced by the kinematic characteristics of the ball, estimated from retinal images (Zago et al., 2009), and from other visual cues providing additional information on the position and velocity during motion as well as other intrinsic characteristics of the ball such as mass, dimensions, and geometry (Lopez-Moliner et al., 2007a,b; Savelsbergh et al., 2002; Shepard, 1994). Moreover, the prediction of the ball trajectory, necessary for fast moving objects, requires knowledge of dynamic behavior of the flying projectile (Shepard, 1994; Tresilian, 1999a,b; van der Kamp et al., 1997; Zago et al., 2009), such as the effect that the gravitational field exerts on the trajectory. The integration of all these sources of information allows the CNS to predict the spatial and temporal evolution of the ball trajectory in space, and to trigger the appropriate motor response to accomplish the task.

However, while catching flying balls in three-dimensional space is an effective paradigm to study sensorimotor coordination, it is generally difficult to control the ball flight parameters. Indeed, the effects that air drag exerts on a flying object induce mathematical complications in the formulation of the equations describing its motion, and in the case of non-linear drag there are no possible analytical solutions (De Mestre, 1990). In previous studies balls were projected by means of commercial launching machines used to train athletes from different sport disciplines such as cricket and tennis (Bockemuhl et al., 2009; Button et al., 2002; Laurent et al., 1994; Mazyn et al., 2006, 2007; Tijtgat et al., 2009; Wann, 1996). In many cases, the experimenter manually positioned the launcher, by trial and error over many test launches, with a specific orientation and manually set the rotational speed of its delivery wheels to ensure desired interception height and flight time at a given distance from the launcher. Such methodology has some limitations. First, it does not ensure standardized visual stimuli at launch. Different flight parameters require different spatial orientations of the launcher and thus different positions of the ball when it is released, unless the pivot of the launching machine is aligned with the delivery hole. In all other cases, as with most commercial launching machines, the position of the launcher must be adjusted as a function of its orientation in order to ensure a fixed ball position at launch time. Second, it does not permit easily randomized sequences of launches. One may want to design an experiment with unpredictable ball trajectories in which participants are asked to catch balls projected each time with different flight parameters. To do so, it should be possible to change the configuration of the launching apparatus quickly and reliably, thus speeding up the duration of the experimental session. Third, it does not prevent visual anticipation due to the visibility of the ball prior to its release, possibly affecting the estimation of response timing. Finally, it does not allow quantification of random flight variability. Non-homogeneous ball surface, possible vibration of the apparatus, and accidental application of initial velocity to the ball during the insertion phase are some of the possible factors unpredictably altering ball launch parameters. Also, the lighter the ball (a desirable feature for safety), the stronger the air drag affects ball motion during flight. Thus, as a certain amount of variability cannot be avoided, it is crucial to monitor the ball trajectory to fully characterize the relationship between motor responses and ball kinematics.

Here we introduce a novel actuated launching system with an automatic launch parameter control that addresses some of the limitations of launching apparatus used previously to investigate catching in three-dimensional space. The system comprises a commercial launching machine and a custom-made supporting structure. The system is actuated and calibrated in order to guarantee the rapid positioning and orientation of the launcher and to ensure the achievement of the desired ball flight parameters without neglecting air drag. Furthermore, the ball trajectory is tracked by a motion capture system. We also present the procedure used to calibrate the apparatus based on a large number of ball trajectories and the results of two validation tests carried out to quantify the accuracy and precision achieved in controlling ball flight parameters.

2. Materials and methods

The launching system has been designed for projecting balls from a fixed initial location to a desired location on a vertical plane, at a given distance from the initial location, and with a desired flight duration. The appropriate ball trajectories were generated by adjusting the initial ball velocity vector, e.g. initial speed (SP), elevation angle (EL), and azimuth angle (AZ) taking into account air drag. The functional relationship between launch and flight parameters was estimated through a calibration procedure based on a large set of recorded ball trajectories. To allow for rapid change and repeatability of the desired flight parameters, the launch parameters (SP, EL, AZ) were set automatically by computer controlled actuators.

2.1. Launching apparatus

The launching apparatus was constructed by mounting a commercial ball launching machine, used to train crickets players, with a fixed launch axis and an adjustable ball exit speed, on a custom-made articulated and actuated structure that could displace and orient the launching machine (Fig. 1). The whole structure was hidden by a large screen with a small hole from which the ball was projected (Fig. 1A). The apparatus also include a motion capture system to track the ball trajectory.

2.1.1. Launching machine

The launching machine (Bola Professional Cricket Bowling Machine, Stewart and Williams, Bristol, UK) had two molded urethane ball delivery wheels, with concave profiles, rotating in opposite directions around two parallel axes that could deliver balls of approximately 7 cm in diameter along a fixed axis (*launch axis*) at speeds ranging from 15 to 95 mph with a resolution of 1 mph. The machine was custom modified by the manufacturer to allow setting the launch speed remotely via an RS232 computer interface.

2.1.2. Positioning structure

The actuated structure used for positioning the launching machine was made of modular aluminum structural framing elements (Bosch Rexroth AG, Stuttgart Germany, assembled by RTC—Romana Trasmissioni Colme, s.r.l., Ariccia, Italy). The structure was composed by a supporting fixed outer frame and three moving inner frames (Fig. 1B). One side of the outer frame was covered with a large screen (4 m × 3 m, width × height, foldable for storage) with a hole of 0.14 m of diameter and center at a height (Z_{exit}) of 1.66 m from which the balls were projected (*launch location*).

The height of the hole could be easily changed by substituting the central panel of the screen. The three inner frames were interconnected through prismatic and rotational joints to provide four degrees-of-freedom to the launching machine: horizontal translation (*Y*, where *X* is the horizontal axis perpendicular to the screen), vertical translation (*Z*), elevation rotation (EL, the angle between the launch axis and the horizontal plane) and azimuth rotation (AZ, the angle between the launch axis and the vertical plane containing the *X* axis). The two translational degrees-of-freedom were required to allow the passage of the ball through the hole with the launching machine at different elevation and azimuth angles. The launching machine was mounted on the innermost frame (frame 1, Fig. 1C) which was connected to the next frame (frame 2) through rotational bearings forming a rotational joint around a horizontal