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Editorial

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Dear readers:

Welcome to the summer 2008 issue of the **International Journal of Computer Science in Sport (IJCSS)**.

There are two sports mega-events taking place this summer. The UEFA **European Football Championship** is currently (June, 2008) held in Austria and Switzerland - an excellent opportunity to apply and test novel tools from information technology.
In less than two months the **XXIX Olympic Games** will be opened in Beijing. Just before the Games, a Joint International Conference of Sports Science and Sports Engineering will be organized in Nanjing, China. There will be one main conference, which is related to Computer Science in Sport (“Pre-Olympic Congress on Computer Science in Sport”). Selected authors will be invited to submit their papers for publication within this journal.

Four original papers and a book review have been included within this issue.

E. Brown and **P. O’Donoghue** apply computer technology for the analysis of coach behaviour. Commercial video analysis packages are used for the analysis and for providing video feedback to the coach.

In the paper by **B. Eskofier**, **E. Hartmann**, **P. Kühner**, **J. Griffin**, **H. Schlarb**, **M. Schmitt** and **J. Hornegger** a system for real-time athlete surveying and monitoring is presented. Special emphasis is given on outdoor and endurance sports.

P. Lamb, **R. Bartlett**, **A. Robins** and **G. Kennedy** investigate the applicability of Kohonen self-organizing maps as a tool to analyze movement variability. Their results support other studies that show self-organizing maps to be effective for classifying movement patterns based on time series data.

A mechanical and mathematical model of sport archery arrow ballistics is proposed in the project report by **I. Zanevskyy**.

A review of Graeme Cohen’s and Neville de Mestre’s book “**Figuring Sport**” rounds off this issue.

If you have any questions, comments, suggestions and points of criticism, please send them to me. Enjoy the summer!

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A Split Screen System to Analyse Coach Behaviour: A Case Report of Coaching Practice

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Abstract

The analysis of coach behaviour using information and communications technology has become an established area of research. Advances in the application of information technology have lead to analysis systems for sports being integrated with match video allowing interactive video feedback to be provided in an efficient and flexible manner. Commercial video analysis packages are not only useful for analysing player behaviour in sport, but can also be used to analyse coach behaviour. The purpose of the current exercise was to implement a coach behaviour analysis system using the Dartfish^{TM} package to allow a netball coach's behaviour to be analysed so that the quantitative breakdown of the coach's behaviour could be supported by video sequences of examples of behaviours of interest within a process of reflective practice. A split screen video displaying a close up view of the coach as well as a wider view of the coaching session was analysed. The coach found the video sequence feedback to be more useful than the quantitative information produced. The specific phases of reflective practice where the system could provide the most benefit are issue identification, experimentation and evaluation.

KEYWORDS: COACH BEHAVIOUR, VIDEO ANALYSIS, FEEDBACK, REFLECTIVE PRACTICE.

Introduction

Over the last 10 to 20 years, information and communications technology has matured to the extent that multimedia systems are applied in many fields including sport. Integrated match database and video feedback systems are used in sport and physical education to provide feedback to athletes to assist the coaching process and skill development (Liebermann *et al*., 2002; Ponting and O'Donoghue, 2004). The advances in information technology that have been exploited in performance analysis packages include the ability to annotate video frames and the use of split screens. Such features have been used in the analysis of sports performance but the use of video analysis systems to analyse coach behaviour has not fully exploited such features (Cassidy *et al*., 2006; Mayes and O'Donoghue, 2006). This paper describes a pilot study to use split screen technology to provide feedback to a high level coach assisting her reflective practice. The paper commences with a brief review of relevant theoretical aspects of coach behaviour, methods used to analyse coach behaviour before describing the exercise to apply and evaluate split screens in the analysis of coach behaviour.

There are different coaching styles that can be used in sport (Jones, 1997). The most effective style depends on the gender of the athletes (Millard, 1996; Lacy and Goldstein, 1990), age group of the athletes (Lacy and Darst, 1985), the type of sport (Massey *et al*.,

1996) and level of the athletes (Jones *et al*., 1995). Sherman *et al*. (2000) found that athletes from male, female and mixed sports had similar preferred to participate in a democratic rather than an authoritarian environment, receiving positive feedback, training and instruction. All three groups reported a similar view that it was not the coach's role to provide social support. Cushion and Jones (2001) found only minor differences between the coaching behaviour used in the top 2 tiers of English soccer with a predominant use of instruction behaviours, praise and periods of silence used as a conscious strategy. The pattern of coach behaviour during training sessions is the use of silent monitoring of the session with intermittent periods of instruction, praise and encouragement. Coaching behaviour is different during training sessions and competition (Chaumeton and Duda, 1988; Wandzilak *et al*., 1988). Indeed in some sports such as elite tennis, coaches are not permitted to provide instruction during matches. Trudel *et al*. (1996) found that ice hockey coaches spent 51% of matches observing without any interaction with the players and that there was little instruction given during competition.

Reflective practice is used in a wide range of industrial, commercial and educational contexts. Schon (1983, 1988, 1991) distinguished between two types of reflective practice which can be used in a complementary way; “reflection in action” and “reflection on action”. Reflection in action is where a practitioner reflects on practice while performing their role. This involves consideration of present experience, feelings and the extent to which experience supports prior understandings. Reflecting on action, on the other hand, is done after a given episode experiencing professional practice. This gives time for experiences to be written up and discussed with supervisors or mentors. It allows questions relating to practice to be considered and ideas for changing professional practice to be generated and plans made for testing those ideas. In a sports coaching context, reflective practice allows coaches to identify and understand issues that have arisen and take measures to address these issues and improve their own coaching. It is important for coaches to understand the cognitive operations that determine their behavior within a coaching context (Abraham and Collins, 1998). Coaches reflect on their practice but this is often an informal process rather than something built into coach development (Knowles *et al*. 2005). Farres (2004) described a structured process of reflective practice that consist of five stages; issue identification, self awareness, critical assessment, experimentation and evaluation. There are a variety of tools and methods that can be used within reflective practice to help the coach learn from experiences. These include the assistance of mentors, coaching logs as well as video analysis of coaching behaviour (Farres, 2004).

There is a growing volume of literature relating to coach behaviour (Miller, 1992; Douge and Hastie, 1993; Harries-Jenkins and Hughes, 1995; Bloom *et al*., 1999; Cushion and Jones, 2001; Smith and Cushion, 2006). Many of the studies have quantified coaching behaviour using methods such as the Arizona State University Observation Instrument (Lacy and Darst, 1984), Coach Analysis Instrument (Johnson and Franks, 1991) which is part of Computerised Coaching Analysis System (Franks *et al*., 1988) and Coaching Behaviour Assessment System (Smith *et al*., 1977). Even though many of these systems had no more than about a dozen defined behavioural categories, reliability of observation of something as complex as coach behaviour is limited. Smith *et al*. (2005) used Gamebreaker (SportsTec, Warriewood, Australia) to analyse coach behaviour and focussed on the 2 out of 5 behavioural classes that they demonstrated could be observed reliably (the percentage error for these two behavioural classes was 2.3% and 3.1% with the remaining behavioural classes having percentage errors of over 60%). However, Smith *et al*. (1977) conducted an extensive reliability study of a system to analyse coach behaviour involving trainee and expert operators, finding that expert observers were the most reliable achieving inter-operator good strengths of agreement with trainee observers ($\kappa = 0.6$ in each case) with 15 of the 19 expert-trainee observer pairs having a very good strength of agreement ($\kappa > 0.8$). The strength of agreement between trainee observers was very good for 120 pairs of observers ($\kappa > 0.8$), good for a further 43 observer pairs ($0.6 < \kappa < 0.8$) and moderate for the remaining 2 pairs of trainee observers ($0.4 < \kappa < 0.6$). Furthermore, Massey *et al*. (2002) found a percentage agreement between independent operators of the Arizona State University Observation Instrument (ASUOI) of over 80% which was considered acceptable.

A further challenge to quantitative systems is that they may over-simplify the analysis of coach behaviour (Strean *et al*., 1997). Gaining a balance between the need for objective reliable information about coach behaviour and the need to understand the complex nature coach behaviour is a difficulty for scientific research in the area. However, quantitative coach behaviour analysis systems can be used in more applied settings along with complementary qualitative techniques. More and Franks (1996) used the Coach Analysis Instrument along with audio and video recordings of coach behaviour and reflective logs within an intervention to help coach development. When such system are used to provide feedback to coaches, the direct evidence to support recommendations made can be effective (More and Franks, 1996). In recent years, many commercial systems have been developed that integrate digital video with a database of timed events facilitating flexible and efficient access to relevant video sequences. These packages are generic allowing them to be tailored for the analysis of many types of behaviour in many application areas. Such systems have not only been used to analyse the performance of athletes in sport but are now being used to analyse coach behaviour as well (Smith *et al*., 2005; Mayes and O'Donoghue, 2006). Cassidy *et al*. (2006) used siliconCOACH $_{\text{TM}}$, Smith *et al*. (2005) used Gamebreaker $_{\text{TM}}$ and Mayes and O'Donoghue (2006) used Focus X2 $_{\text{TM}}$ to analyse coach behaviour. The advantage of using video is that it assists the coach recall events during coaching sessions they are reflecting on (Gilbert and Trudel, 2001). The advantage of using commercial video analysis packages is that the process becomes more flexible and efficient with immediate access to video sequences of any events satisfying the user's criteria.

The purpose of this study was to test the use a commercial video analysis package within the process of reflective practice of the coach in order to evaluate the system based on inter-operator reliability for the system, the views of the coach about the usefulness and applicability of the system within reflective practice for the coach as well as the experience of the efficiency of using the system.

Methods

Overview

A high level coach of players in an international academy based at the university where the authors work, participated in the current case study. The coach was a 26 year old, level 3 netball coach who has been coaching for 6 years at club, university, National Super League club and international academy levels. The coach was recruited by direct request due to her genuine interest in sports science and technology support for the coaching process. The athletes involved were female international academy players whom she had been coaching for 2 years. The schedule coaching sessions during the mid competition season (January to February 2007) to be undertaken by the International Academy squad were described by the coach and one particular session was selected because it was planned to contain technical elements and simulated game situations. The selected session was a 60 minute coaching session that was composed of four broad sections; (a) ball handling drills by small groups of 3 players for 31 minutes, (b) moving and passing drills by groups of 6 players for 11 minutes, (c) moving and passing drills involving all players in the session with 2 balls in play for 8 minutes and (d) 10 minutes of simulated game situations. Each of these subsections included pauses for drink breaks, coach instruction and demonstrations. The session was video recorded using 2 cameras, one focussing on the coach and the other recording a wider view of the players training as well as the coach. The videos were indexed using the Dartfish package (Dartfish Europe, Fribourg, Switzerland) allowing quantitative and video sequences to be presented to the coach to assist her reflective practice. The coach provided feedback to the authors about the usefulness of the system which was analysed together with the authors' experience of producing the statistical and video material within an evaluation of the exercise.

Video Capture

Two cameras were used to video record the coaching session from a fixed elevated position so as all areas of the session could be captured, with little obstruction. The two cameras were operated by two different people. The first camera focussed solely on the coach to provide close-up views of what the coach was doing during the session. This camera also had the radio receiver attached so that all verbal communication made by the coach would be transmitted to and recorded by the camera over any other noise. The coach wore a microphone which was attached to her shirt with the radio transmitter fastened to her belt allowing her to move freely around the court and able to use her hands to perform full demonstrations. The second camera was positioned to the side of the first and was used to record a full view of the session so when analysing the coach's behaviour, situations leading up to a coach's interventions and the actions that followed could be examined.

Video Preparation

The videos were downloaded onto the computer and synchronised using the Dartfish package. A single split view video was saved with the coach close-up view on the left hand side and the wider coaching session view on the right hand side. The sound recorded from the coach's microphone and the split screen video were merged within Microsoft MovieMaker version 5.1 (Microsoft Corporation, Redmond, Washington, USA) before being saved and loaded back into Dartfish for analysis.

Tagging

The tagging facility within Dartfish allows a video to be indexed with timed sequences of events. The Dartfish package is used typically to analyse sports performance as well as educational contexts. Within the current study, the Dartfish package was tailored so as details relating to coach behaviour could be recorded. To establish the types of events and other details that could be recorded, it was necessary to observe the video noting key behaviours and aspects of those behaviours to be recording. During the initial stages of this pilot study, the event types used in other coach analysis systems were considered (Bloom *et al*., 1999; Harries-Jenkins and Hughes, 1995; Mayes and O'Donoghue, 2006). The event categories used by Mayes and O'Donoghue (2006) were considered during a pilot viewing of the coaching session by the authors. This pilot viewing together with consideration of Bloom *et al*.'s (1999) coach behaviour classification scheme lead to many changes to the system used by Mayes and O'Donoghue (2006). The audience and type categories used by Mayes and O’Donoghue remained unchanged. However, the behaviour and style categories were merged into a more extensive behaviour category and the content and player behaviour categories merged into a new aspect category. The appropriateness category was removed but a new mode category added to represent broad behaviour types. The final event categories are summarised in Table 1. It was recognised that these categories were not mutually exclusive. However, even simpler classification schemes such as the ASUOI (Lacy and Darst, 1984) are not entirely mutually exclusive. The benefits of the proposed classification scheme were considered to outweigh the disadvantage of not being mutually exclusive.

Table 1: The final category set used for tagging with operational definitions.

Category	**Option**	**Definition**
Audience	Team	Addressing the whole team
	Individual	Addressing an individual
	Sub - group	Addressing a subset of the team
Mode	Visual	Watching or observing
	Verbal	Talking to players
	Physical	Motion or placement
Behaviour	Assistance	Action to help player(s) positioning or technique
	Demonstration	Providing a visual representation of the action desired
	Description	Providing a verbal description of the action desired
	Encouragement	Providing praise or hustling the action
	Evaluation	Providing verbal feedback relating to the quality of player action
	Explanation	Providing a rationale for action required or reasons why action resulted in outcomes experienced
	Instruction	Providing a precise direction as to the action required
	Interrogation	Questioning players about the way action was performed or checking understanding
	Observation	Watching the action without comment
	Organisation	Directing or placing athletes or objects in desired positions
	Reconstruction	Providing visual representation on actions that have been performed by the player(s)
Type	Positive	Behaviour focussing on positive aspects of player behaviour
	Negative	Behaviour focussing on negative aspects of player activity
	Neutral	Neither focussing on positive or negative aspects of player activity
Aspect	Technical	Skill related
	Tactical	Related to player decision making
	Practice	Related to performance of drills
	Other	Not related to the activity performed in the session

The final user interface is shown below in Figure 1. The Dartfish package was set up to provide buttons representing the different aspects of coach behaviour identified in Table 1. The user was allowed to enter events of varying durations during the tagging process. The system also allowed overlapping events to be entered. The full 60 minute coaching session was tagged with all verbal and behavioural events that could be accounted for by the category set shown in Table 1. The procedure used to analyse the session involved considering each event using the following four steps:

1. Observing the video recording of the behaviour as many times as was necessary to decide on option to choose within each category.
2. Selecting the chosen options.
3. Identifying the beginning and end of the behaviour and tagging the behaviour in Dartfish.
4. Viewing the tagged video sequence to check that the most relevant options for each category have been selected.

Following the completion of the tagging process, the event sequence stored in Dartfish was exported for further analysis in Microsoft Excel. The Dartfish-based system allowed interactive video feedback to be provided and also allowed selected video sequences that satisfied user criteria to be exported and included within a stand-alone highlights video produced in Microsoft MovieMaker. The process of selecting video clips to include consisted of the following 5 steps:

1. The various pairs of categories were cross-tabulated and inspected by the authors.
2. Examples of coach player interactions that would assist the coach’s reflective practice were interactively viewed and the best examples were selected.
3. The selected clips were saved.
4. The saved clips were imported into Microsoft MovieMaker.
5. The clips were trimmed, arranged into a logical order with titles being added and statistical information added so as they would be presented with related video clips within the movie. The movie was saved as a media file that could be viewed without using Dartfish.

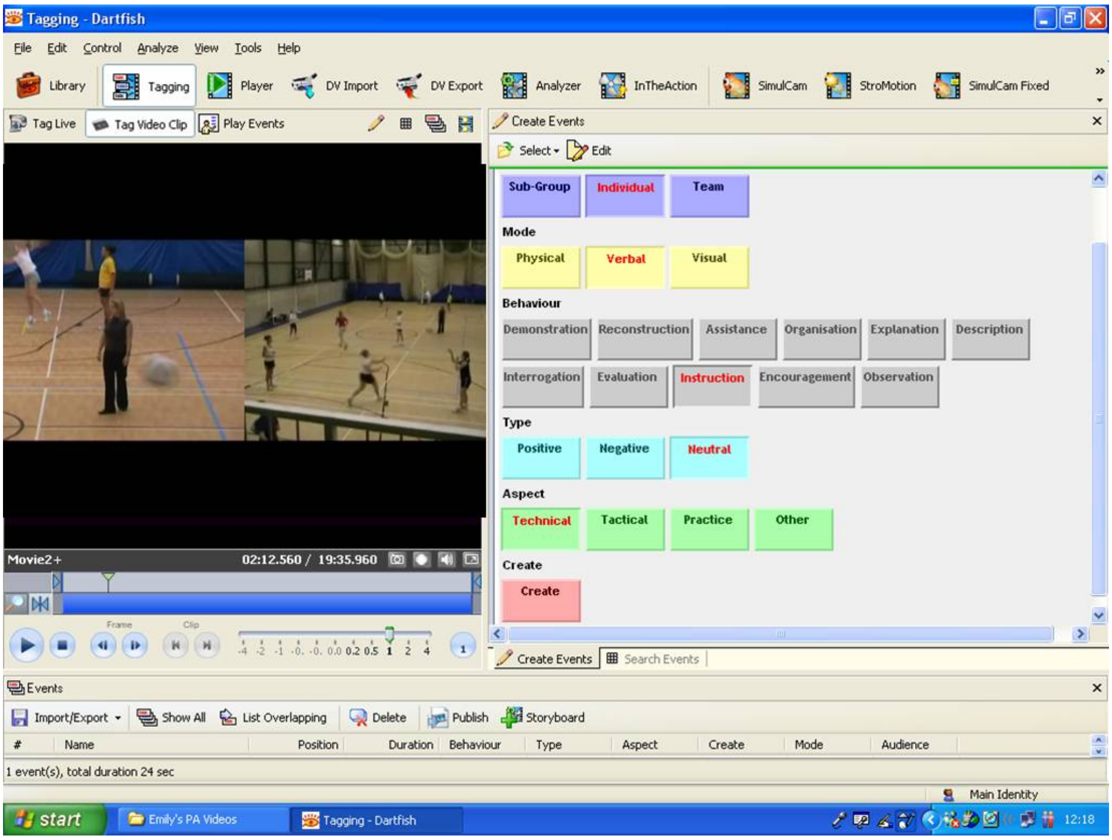

Figure 1**:** User interface screen as used during the tagging of the split screen video.

Reliability

The system is a lapse time system with analysis done after the coaching session is video recorded and the split screen version of the video produced. A 20 minute sub-section of the 60 minute split screen video of the coaching session was analysed independently by each author of the current paper. The 2 recorded event sequences were exported for comparison. One of the authors recorded 99 events while the other author recorded 169 events; there were 88 events that were recorded by both authors. Inspection of the 2 event sequences revealed that most of the additional events recorded by the second author resulted from occasions where the behaviour of the coach was interpreted as a single event by the first author but as more than one shorter event by the second author. The kappa statistic was computed for those 88 events recorded by both authors. The strength of agreement between the authors was interpreted using the classification scheme proposed by Altman (1991, p. 404) for kappa. Aspect was agreed on 59% of occasions but the kappa value of 0.129 revealed a poor strength of agreement. There was a good strength of agreement for audience (85.2% of events, κ = 0.761) and type (79.5% of events, κ = 0.666) and a moderate strength of agreement for behaviour (64.8% of events, κ = 0.559) and mode (86.4% of events, κ = 0.453). The limited reliability of the system is unsurprising given the multi-dimensional analysis system, the limited reliability achieved by simpler systems for analysing coach behaviour (Smith *et al.*, 2005) and the fact that may aspects of coach behaviour overlap (Mayes and O'Donoghue, 2006) leading to events being interpreted in different ways. The authors, therefore, advise against the quantitative data presented in the current paper being referenced as being typical for netball coaching.

Evaluation Study

The split screen video of the complete 60 minute session was analysed by the primary author of the paper. A stand-alone video was produced containing examples of the most commonly occurring coaching behaviours as well as less frequently occurring behaviours that would be useful for the coach to reflect on. This video was 4 minutes 34s in duration and synergetically included statistical information along with related video sequences. The video was provided to the coach who observed it on her own laptop computer (screen size 28.1cm x 21.6cm). The coach was also provided with a 60 minute movie as a media file on a CD which showed the complete session using a split screen view. The coach was able to look at tables that cross-tabulated different pairs of variables and consider the frequencies. She was able to look at video sequences of events of interest. The authors met the coach a week after the video and statistical information had been provided in order to discuss the videos. The events of interest to the coach were communicated to the authors who translated these into criteria to enter into Dartfish to view related video sequences.

An informal discussion took place over a period of 45 minutes where the coach provided feedback on the information produced and how it could be helpful to her reflective practice. This was not a formal interview and the discussion was not recorded verbatim. The discussion had four main sections. Firstly, the 4 minute 34s highlights video was observed to display different examples of coaching behaviour. This prompted an initial 5 minute discussion about behaviours that the coach was and was not aware of. The second part of the discussion was used by the coach to clarify what kinds of behaviour were being counted under which class of behaviour when the split screen video was analysed. This took about 10 minutes with the coach also making suggestions about the tagging process used. The third part of the discussion was a brief 5 minute discussion of the usefulness of the statistical information before the fourth part which was a 20 minute discussion relating to the split screen video view of coaching behaviour as it was provided in the full unedited 60 minute video and the 4 minute 34s highlights video. Notes were recorded by the authors so as the main points made by the coach could be included within the evaluation of the system. The authors then discussed the experience of producing the video, noting advantages and disadvantaged of the approach. The points made by the coach and the observations of the authors were considered together within the evaluation of the system. Four main themes emerging during the evaluation study; (a) the quantitative information, (b) the video information, (c) stages of reflective feedback where the system used could be beneficial and (d) the effort required to produce the split screen based feedback.

Findings

Quantitative information produced

An important finding to report in the current investigation is the effort required to produce the quantitative and video feedback information for a 60 minute coaching session. Prior to the observation of the coaching session, it was necessary to make arrangements to use all of the necessary equipment, ensure batteries were fully charged and test the microphone and radio transmission to the camera. Loading the two 60 minute videos into Dartfish required 2 hours and then a further hour was required to synchronise accurately and add the correct sound source. The split screen video then had to be saved (which took 4 hours of computer time) before being reloaded into Dartfish for tagging. The primary author required 3 hours to tag the entire 60 minute coaching session. Once the quantitative information was considered and the types of video sequences decided, it took 2 hours to produce the 4 minute 34s stand-alone video. Once all of this activity was complete, the authors were ready to present quantitative and video sequence information to the coach. It was possible to produce different types of quantitative information about the coach's behaviour including frequencies, time duration and percentage of session time for each behaviour, mode, audience, type and aspect. Table 2 is an example of the amount of time spent performing different behaviours.

Table 2. Time durations of each behaviour during the observed session.

Behaviour	Time Duration
Demonstration	1 min 50s
Description	2 min 05s
Encouragement	0 min 57s
Evaluation	1 min 10s
Explanation	0 min 48s
Instruction	3 min 03s
Interrogation	2 min 50s
Observation	3 min 23s
Organisation	0 min 35s
Reconstruction	1 min 15s

Coach's Feedback

The coach did not find the summary quantitative information to be useful. Firstly, there was no normative information to compare the frequency, duration or percentage time profiles against. This makes it impossible to understand whether the values were low, average or high for the type of session observed. The coach also made the point that the events of a given type that were counted varied in importance within the session. The quality of the coaching behaviour within the events was not apparent from the quantitative information. The coach also believed that it would have been better if the coach tagged her own behaviour rather than an independent analyst doing it; the reason given for this was that the coach would have a better chance of recalling what she was thinking about and looking for during the periods of silent monitoring that preceded periods of intervention and communication. Knowledge of the coaches thoughts during these periods would have an impact on how communication events could be interpreted using the system.

The coach had seen the system used by Mayes and O'Donoghue (2006) and recognised the improvements made in the current system. The specific improvements that were helpful to her reflective practice were the split screen view and being able to hear her own voice during the video playback of the coaching session. This provided a better platform for the coach to analyse her own coaching behaviour and methods. She felt it was beneficial to be able to see her body language during the session. Having the split screen and the ability to watch selected clips from the session allowed her to watch the clip firstly looking at herself as a coach and then for a second time looking at the athletes. This allowed her to gain a greater understanding of what she thought she was communicating to the players and what the players were actually hearing and then doing. Although there was a positive reaction towards the video information provided, the coach identified further improvements that would be beneficial. It would be useful to zoom in closer to the coach so that facial expressions could be observed; she viewed facial expressions as being just as important as other aspects of body language, actions and speech. She also felt that it would be beneficial for the session camera to focus on individuals or sub-groups being addressed rather than covering the whole area all of the time. The reason given for this was that the players' body language, facial expressions and actions would be clearer allowing a better analysis of how well the coach's comments and instructions were being understood by the players.

The way in which the video information could be used by the coach was also an area where the coach provided interesting and useful feedback on the methods used. The 4½ minute stand-alone video produced was useful to give examples of different types of behaviour and should be seen before any quantitative information is shown to the coach. The coach found actual video sequence examples to give a much better meaning of event types than the text definitions used in Table 1. This is because different people reading the same words could have different interpretations of what was actually meant by those words. The interactive feedback was useful to efficiently view video sequences related to particular aspects of coach behaviour. However, the coach believed that viewing the full 60 minute split screen video of the coaching session was more important to allow her to analyse temporal patterns of coaching behaviour and how particular aspects of the session were addressed as the session progressed.

The five stages of reflective practice identified by Farres (2004) are issue identification, self awareness, critical assessment, experimentation and evaluation. The coach discussed how the system could be helpful in reflective practice during these various stages. Issues could be identified using the system as it provides statistical and video sequence feedback in additional to the experience of the coach during the session. The coach reported that it could make her aware of subtle aspects of body language that she might not have been aware of without the video information. While the video information did help identification of issues that could then be critically assessed, the coach did not see a direct contribution of the system to the critical assessment stage of reflective practice. The system did have potential for use in experimentation if various solutions to issues being applied within coaching sessions could be video recorded for further analysis and evaluation. Where evaluation was being assisted by a mentor, the ability to review and discuss video sequences was considered beneficial. While the quantitative information was not seen as directly important to reflective practice, the importance of having a tagged video allowing interactive and efficient viewing of relevant video sequences was recognised.

The time-series nature of the coach's behaviour made analysis of temporal patterns within the data important. Inspection of the order of events recorded supports the finding of Cushion and Jones (2001) that communication events are interspersed with periods of silent monitoring with 56.7% of coach behaviours being preceded by periods of silent observation. Indeed, those events that were followed non-observation events could be considered as higher order coach communication events composed of descriptions, explanations and encouragement for example. There were few other repeating patterns within the data, although different parts of the session commenced with instruction to the team and ended with varying numbers of evaluation events; for example there were 2 parts of the session where a single evaluation event involving a single player were recorded while there was another part of the session where there were 17 evaluation events recorded throughout the duration of this part of the session with 8 other observation, encouragement, explanation, assistance and description events. This variability in temporal pattern of coaching events between different parts of the session can be explained by the coach having to address different facets of player performance in appropriate ways during different parts of the session.

Discussion

The purpose of the current investigation was to evaluate the use of a computerised video analysis system to analyse coach behaviour and its potential within reflective practice. The particular results presented here in Tables 2 should not be generalised beyond the particular coach within a particular session and also the limited reliability of the observation should be considered. The use of such systems clearly requires considerable observer training to yield reliable results (Gilbert and Jackson, 2006). However, the coach suggested that if she tagged the video herself, she would have more of an understanding of her thoughts and reasoning during the session. Such a tagging exercise would also allow the coach to consider different events in turn and reflect on them in detail when deciding on how to classify them with the system. This would assist in identifying some issues within the first stage of the reflective practice approach described by Farres (2004). The quantitative information produced would be of most use in allowing video sequences to be efficiently accessed and played back by the coach and any mentors observing. The role of the mentor in discussing and evaluating issues (Gilbert and Trudel, 1999) would be greatly enhanced by the ability to do this and would not require the mentors to be present at the coaching session itself. The quantitative information simply confirms that coaching often involves silent observation with periodic instruction so as not to overload players or dilute main feedback points (Hodges and Franks, 2002). One aspect of coach behaviour not covered in the current system is timing of feedback which is critically important to correcting faults (Dick, 2003). Detailed quantitative information may require normative information to aid interpretation. When one considers the number of factors that influence coaching style (Metzler, 2000), a substantial amount of research would need to be done to provide such norms for all combinations of age, level and type of session for the given sport. The research to produce such norms would need to be done by trained observers who could reliably use the system. Indeed, the number of different categories in the current system, while useful to the individual coach, may be too much for reliable observation to be possible. Therefore, a standard behavioural analysis scheme such as that of the Arizona State University Observation Instrument (Lacy and Darst, 1984) may be preferable.

The video sequence feedback was found to be more beneficial to the coach than the quantitative information about her behaviour. The identification, experimentation and evaluation stages of reflective practice can all be supported by the availability of such information (Farres, 2004). Subtle aspects of body language can be recognised during the review of videos of coaching practice. Reflective practice uses different tools and techniques to assist the coach and the use of computerised video analysis systems should be supplemented by other means of facilitating reflection (De Marco *et al*., 1997; Potrac *et al*., 2002; Cunningham and Dixon, 2003). It is also worth noting that reflective practice should address all facets of coaching in need of attention and not just coach behaviour. Coach knowledge and strategies are not merely a separate issue of coaching to be considered during reflective practice, but may be determinants of observable coach behaviour (Côté *et al*., 1995). A further aspect of coaching that needs to integrated with coach behaviour within the process of reflective practice is the cognitive assessment of coaches that explain many of the behaviours used by coaches (Abraham and Collins, 1998). While the computerised video analysis system allows behaviour to be reviewed, other complementary techniques such as discussions with mentors are needed to reflect on the decision making processes that occurred during silent monitoring periods of coach sessions.

The process described in the current investigation was quite time-consuming and this is something that a coach would need to consider if using such an approach, especially with the split screen view. The split screen was more time consuming to produce than if a single view was used such as those used in the studies by More and Franks (1996), Mayes and O'Donoghue (2006), Smith *et al*. (2005). The benefits of such an effort would need to justify the time and cost. The benefits identified by the coach include being able to analyse body language, player reactions and have a greater volume of video information relating to the coaching session. The usability of these systems has improved with technological advances (Liebermann *et al*., 2002) and this will help promote their use in coach reflective practice in future.

Conclusions

Computerised performance analysis systems such as Dartfish and the ability to create a synchronised split screen video which can be tagged support flexible and efficient access of video sequences that can be used within a coach's reflective practice. The summary statistics were not found to be useful by the coach and also suffered from limited reliability and a lack of normative data to compare the coach's behavioural profile with. The ability to produce interactive video provides evidence of different coach behaviours allowing a more in-depth analysis of coach behaviour including subtle aspects of body language and facial expressions. This type of feedback is not only useful for individual coach reflection but can also be discussed with mentors.

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Real Time Surveying and Monitoring of Athletes Using Mobile Phones and GPS

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Abstract

We developed a system for real-time athlete surveying and monitoring with emphasis on outdoor and endurance sports. The goal of our work is to provide a lightweight, non-hindering and highly mobile application that is capable of getting real-time information from an athlete about the physiological state and the prevailing workout situation, also focusing on its subjective perception.

To provide this system, we implemented a software solution tailored to the task of online surveying and data recording on a standard mobile phone. In order to prove the usability of our design, it was used in a one hour running study with 84 participants. Self-rated information about the psychological state of the athletes as well as speed and GPS position information was collected specifically for this evaluation. We visualized the collected data in a combined way, integrating the speed and subjective state information in a joint representation together with terrain data and maps. The system proved to be highly reliable in practical use. Moreover, the majority of the study participants stated that the additional equipment was not hindering to their sports activity.

KEY WORDS: MOBILE PHONE, GPS INTEGRATION, SUBJECTIVE SURVEYING, JAVA MOBILE, DATA VISUALIZATION

Introduction

Information about the subjective feeling of athletes is very important for many domains. One example is sports product testing. Details such as appearance, functionality, handling and ergonomics are important points that have substantial influence on the choice of the customer. The subjective feeling of athletes concerning their equipment therefore is an important criterion for the success of a product. Another example is perception research, where information about the perceptive state of an athlete is collected over a longer period of time. Training and performance optimization can also benefit from this information.

The common problem is to access the desired information while the athlete is in a typical situation. Real-time surveying is of course possible in a lab environment, e.g. on a treadmill. This has already been done for example by Acevedo (1996) and O’Halloran (2004) in psychological studies. The obvious disadvantage is that the results are biased due to the nonnatural lab situation. The more normal situation of a long distance outdoor run, for example, is much harder to assess because direct contact to the athlete is complicated or not possible at all. In most cases, the desired subjective as well as objective information is collected after the respective sports activity. Abele and Brehm (1985) have done this in a study where they wanted to assess the change in the mental state of athletes caused by a set of different sport activities. The participants had to answer questions concerning their subjective actual feeling-states before and after a 60 to 90 minute course of physical activity. When following this procedure, part of the information is lost because it is not possible for the athlete to memorize all individual details of his perception. It is more desirable to access the desired information at certain time points or after reaching for example a certain waypoint on a predefined route in real-time.

To achieve this, we designed and implemented a system for the surveying of runners using mobile communication equipment, i.e. a standard mobile phone. For this specific project we decided to use the Java Platform, Micro Edition (Java ME, Sun, 2002b, 2007) as programming language because it is implemented on most mobile phones. The advantages of the cell phone hardware platform are manifold. It is lightweight, mobile and highly configurable. There is no extra cost associated with hardware development, only the software has to be adapted to the specific requirements at hand. Most mobile phones are highly suitable because of their advanced computational power. Communication and real-time data transmission could also be implemented easily if desired.

The system we implemented fulfills the following requirements:

- Predefined questions are handed over to the system as audio files, associated answers are recorded.
- The athlete is asked the questions at certain predefined time points.
- Alternatively we implemented the option to react to certain external events. This includes for example significant changes in running speed or altitude and the achievement of waypoints. External hardware like GPS receivers can be connected to the phone via Bluetooth to enable this.
- Headsets can be connected to the mobile phone via Bluetooth as well to assure maximum comfort for the athlete.
- If desired, arbitrary audio files (music) can be played between the question units for the purpose of motivating the sportsman.
- Configuration of the system is possible both directly on the cell phone or a personal computer.
- Once the configuration is completed, the software requires no further interaction. That way, it could be used at anytime that is convenient for the test person. Starting the predefined survey program requires only the press of a button.

We will give a short overview of previous work on the topic of athlete monitoring. In the following, the important building blocks of our system will be explained. We will also show an experimental evaluation of our mobile monitoring solution with 84 runners. This evaluation was done within the scope of a larger psychological study for which subjective information during a one hour outdoor run was needed. As a result and conclusion we will show that our system is highly reliable, providing very valuable information about the psychological and physiological state of an athlete.

Previous Work

The authors know of no previous work that aims at implementing a sports monitoring and surveying device by using the capabilities of a mobile phone. There are, however, several publications that deal with the same topic. An obvious example are telemonitoring devices that rely on radio transmission. Wang et al. (1992) showed the application of such a device in shell rowing. The disadvantage of such systems is that the athlete might get out of transmission range and information would be lost. An extensive review by Armstrong (2007) gives an overview about other applications of wireless connectivity for health and sports monitoring. None of the reviewed publications implements a method for getting real-time feedback about the subjective state of an athlete.

Hallberg et al. (2004) present a system that monitors heart rate and location of an athlete via GPS. The information is sent via GPRS to a media server that provides an enriched media experience to viewers of sports events. They also showed the practical usability in an example for cross country skiers. However, no direct audio feedback from the athlete concerning the subjective fitness and psychological state is featured.

Another application of GPS and physiological information was presented by Saupe et al. (2007). They also use Google Earth for the visualization of physiological parameters as well as information about endurance sport training activities on a large high resolution display. In contrast to our work, no direct subjective information is acquired for the analysis.

Methods and Materials

Java Platform, Micro Edition

One of our framework requirements was that our software should work with a broad range of mobile phones. The Java Platform, Micro Edition (Java ME) is preinstalled on most phones and therefore fulfills this requirement. We consequently chose this software platform for our implementation.

The capabilities of an environment for the Java Virtual Machine in the Micro Edition are defined by three important building blocks, see Figure 1. The most basic is the device configuration. Most common for mobile phones is the Connected Limited Device Configuration (CLDC) as specified by Sun (2007). It specifies the minimum hardware requirement. In the current version 1.1 these requirements include a 16-bit or 32-bit processor, 32 kByte RAM and at least 160 kByte non-volatile memory. The high level programming interfaces are defined by profiles. The Mobile Information Device Profile (MIDP) is built on the CLDC and offers basic APIs for programmers. The current version 2.0 (Sun 2002b) offers user interaction classes, security management and basic file connection capabilities. The third important building block for software development on mobile phones are the optional APIs. Phone manufacturers can decide which of these packages called Java Specification Requests (JSR) they want to implement on their devices. Factually, a lot of these additional packages are standard and can be used on most phones. Important optional APIs for our software are the:

- Mobile Media API (JSR 135, Sun 2006b) for playing and recording sound files and video processing.
- File Connection API (JSR 75, Sun 2004) for file handling.
- Bluetooth API (JSR 82, Sun 2002a) for Bluetooth connectivity.
- Location API (JSR 179, Sun 2006a) for position determination.

Applications that build on the MIDP and any of the optional blocks are commonly referred to as MIDlets.

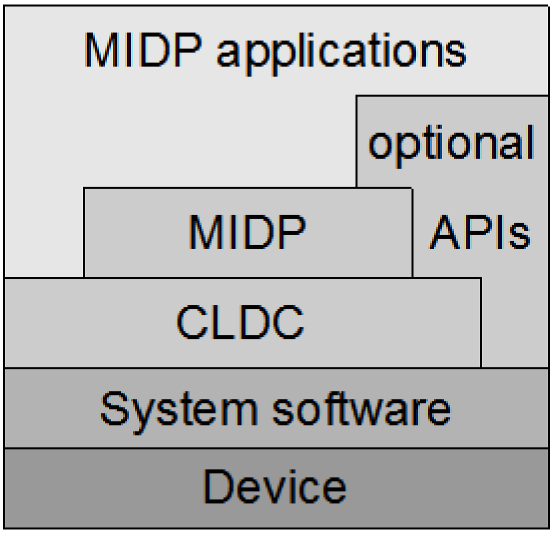

Figure 1. High level Java ME architecture view.

Mobile Phone Hardware

For the development of our MIDlet software we had to restrict ourselves to mobile phones that offer a CLDC 1.1 compatible hardware and MIDP 2.0 with the optional APIs as stated above. Most of the current cellular phones fulfill this requirement. We wanted to show with our reference implementation that our software is working on different types of mobile phones. The companies Nokia and Sony Ericsson offered the best online support for developers, we therefore chose a Sony Ericsson W850i, a Nokia N70, a Nokia E50 and a Nokia 6110 Navigator, see Figure 2. Each of the selected devices offers a slot for memory cards and thus enough capacity to store information even for very long studies. The phones are all lightweight and have high battery capacities for more than 4 hours of active use.

Figure 2. Selected phone models. From left to right the Sony Ericsson W850i (116g), the Nokia N70 (126g), the Nokia E50 (104g) and the Nokia 6110 Navigator (125g) are shown (Nokia, 2007 & Sony Ericsson, 2006).

Development Environment

Both selected phone manufacturers offer developer tools that provide device emulators and advanced debugging capabilities. This is very important for MIDlet development because error identification on the mobile platform can be very tedious. The software development itself was done with NetBeans 5.5 with mobility pack. The manufacturer SDKs can easily be integrated in this development environment, additional tasks like code obfuscating and optimization are thereby provided.

Implementation Details

Software Structure

The evaluation system had to be easily configurable and very flexible in order to support a lot of different devices and study options. Questions and position data had to be recorded as well as predefined sound files played to the athletes. The software had to work with minimum preparation time and no user interaction at all once the tests were running. The building blocks of our software that are shown in Figure 3 will be explained in the following.

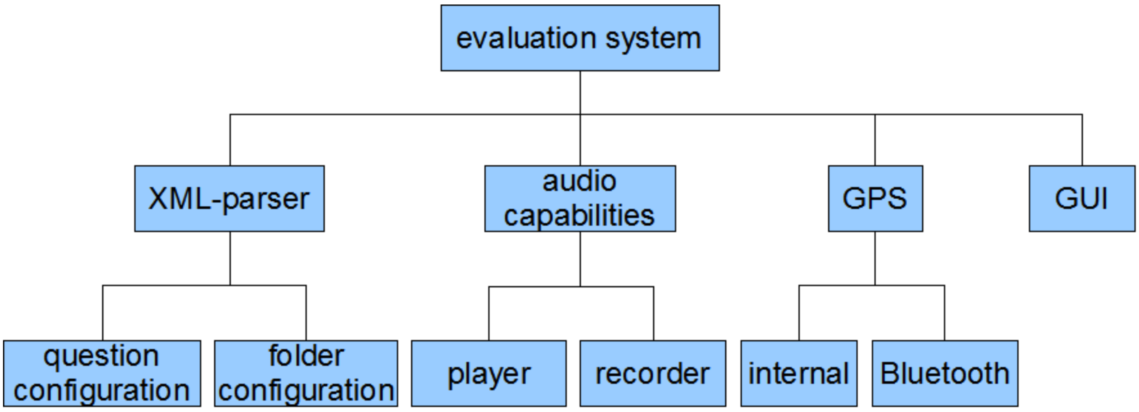

Figure 3. Structural diagram of the software for the evaluation system.

XML-Parser

The configuration of question units and storage location for the recorded sound files and position information was done with a XML file. Additionally, we stored information like start time, recorded files, identification number of the mobile phone and other information in a XML info file after the survey was completed. Because XML parsing is only supported by JSR 172, which is seldom implemented, we had to come up with our own parser.

The system can be configured to play sound files at certain time points or in reaction to external events, e.g. when a predefined distance has been covered. Subsequent to the questions, answers can be recorded, in this case a short sound is played at the beginning and the end of the recorded time span. The system can also be configured not to record after playing a sound file in case the athlete should be briefed, e.g. to decrease the pace. Another option is silent recording, i.e. recording without playing any sound at all. We used this option to capture the breathing noise of the runner in order to be able to determine the respiratory frequency.

Audio capabilities

The audio part supports threaded playing and recording in order to allow for example seamless position information storing even during question units. The configuration is done in one single XML file. In case there is an overlap of sound files, i.e. in the event that the combined playback and recording duration is longer than the span to the desired start of the next unit, this overlap is automatically resolved. Figure 4 illustrates this further. The order of the question units in the configuration file defines the precedence for the overlap resolution.

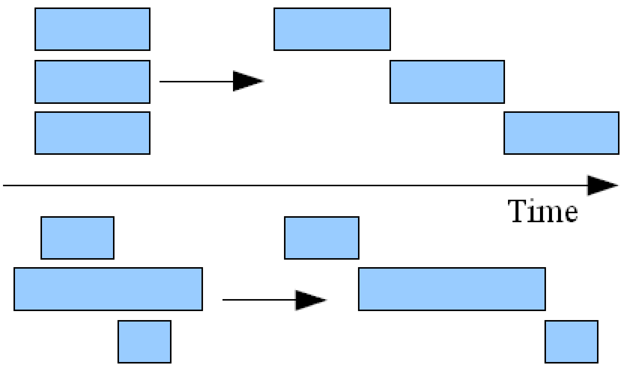

Figure 4. Overlap resolution. Audio files are played in the order that is defined in the configuration file.

The audio codec is automatically selected dependent on the sound files to play. For recording, we used a codec suited for speech. We found that a bit rate of 128 kbit per second with a sample rate of 8 kHz was sufficient for our purposes.

GPS Integration

GPS integration was an integral part of the software development in order to have access to speed, altitude and position information. The software works for phone models with integrated GPS like the Nokia 6110 Navigator as well as with an external GPS receiver (e.g. a Nokia LD-3W) connected via Bluetooth. The GPS data is sent in an interval of approximately one second, which is sufficiently precise for the purpose of recording running position information. Each sample consists of longitudinal and latitudinal position information, speed of movement, altitude, time information and various precision and validity parameters.

The data is stored in the original NMEA (National Marine Electronics Association) format (Langley, 1995), as well as directly converted to the KML (Keyhole Markup Language) format used by Google Earth. This conversion allows for a quick and easy method of visualizing the run. Run parameters like speed and psychological state can be represented as height above ground (see Figure 5 in the results section) or color coded.

Graphical User Interface

The GUI that we developed extends the limited window manager provided by Java ME. It allows changing several configuration options, to connect to the internal or external GPS device and view the current position information. Once the surveying process is started, no further user interaction is required in order to minimize interference with the athlete.

Experiments

Experimental evaluation of the system was performed in the context of a psychological study with 84 runners in Portland, Oregon (USA). While the details of the study itself are beyond the scope of this paper, the relevant points for the evaluation of our mobile surveying system will be given.

The objective of the study was to appraise the subjective feelings of the runners during a recreational run. Each athlete participating in the study was asked to run outdoors for one hour. They could freely choose their preferred route and speed as we could record these parameters with the GPS signal. We chose to use the Nokia 6110 Navigator cell phones for the purpose of this study as they have an inbuilt GPS receiver. This prevented that the runners had to carry an external GPS receiver as extra equipment. The phones were placed in a belt that was attached to the upper arm of the participants. The runners also wore a Bluetooth headset to ensure maximum comprehensibleness.

Before starting the run, an audio file with instructions was played to the participants, followed by a first set of 8 questions. After each question, a short sound was played to indicate the start of the recording interval. The end of the three second recordings was marked by another sound. The athletes were instructed to answer each question about their subjective state with a self-rated grade as given in Table 1. An example question is “Do you feel motivated?”.

Table 1. Grades for the athlete self-rating.

Spoken answer	Meaning
0	not at all
1	very little
2	little
3	somewhat
4	rather
5	very
6	extremely

Directly following this first question unit the runners were asked to start their one hour run. During this run, question units identical to the first one were posed with an interval of 5 minutes between the start of each unit. A total of 13 question units with 8 answers per unit were thus recorded for each athlete.

Results

The mobile surveying system worked without technical difficulties for all 84 runners. A total of 8736 sound files with self-rated subjective state information were recorded. We transcribed the audio files by listening to them and then manually entering the spoken answers in a data matrix. We found that 355 sound files (4.1%) were unusable, i.e. containing no meaningful answers. The main reason for this was that at the beginning of the study, we did not clearly enough emphasize the fact that the answers should be spoken in between the two sounds indicating the recording time. Consequently, a lot of runners spoke their answers right after the questions were asked when we started the evaluation. We therefore changed the set of instructions after the 19th participant so that the record interval was clearly explained. After this change, only 62 entries could not be acquired, mostly because the runners were exhausted at the end of their runs and did not answer in time. In summary it can be said that as long as the athletes gave their answers during the recording time, the information was audible and could be transliterated. No audio sample was lost due to malfunctioning of the mobile phone.

We also collected a questionnaire after completion of each run. Among other details, we wanted to know how much impeded the athletes felt by the additional equipment. The results can be seen in Table 2. It can be seen that most runners perceived the cell phone and headset as very little or little impeding. Only 4 out of 84 athletes found the equipment to be hindering.

Table 2. Impediment by the additional equipment as perceived by the 84 study participants.

Perceived Impediment	Number of runners
very little	51
little	29
some	2
much	2
very much	0

It was also very important that the GPS signal recording worked in order to get reliable position and running speed information for our study. After analysis of the recorded data, we found that only 0.07% (173 out of 260214) of the position samples were unusable. Because of the fact that in no case two consecutive samples were missing, it was straightforwardly possible to interpolate the unavailable position information with a linear estimation strategy.

Figure 5 illustrates the GPS information for one example runner. The chosen running track and speed can easily be analyzed. We can also show the subjective states, in the example of Figure 5 the state of perceived fatigue is displayed. It can clearly be seen that the perceived tiredness is increasing during the run. This visualization allows for a straightforward and convenient analysis of the interplay between various parameters like elapsed time, speed, elevation circumstances and subjective state. Additional data, e.g. heart rate, can easily be integrated into the visualization if present.

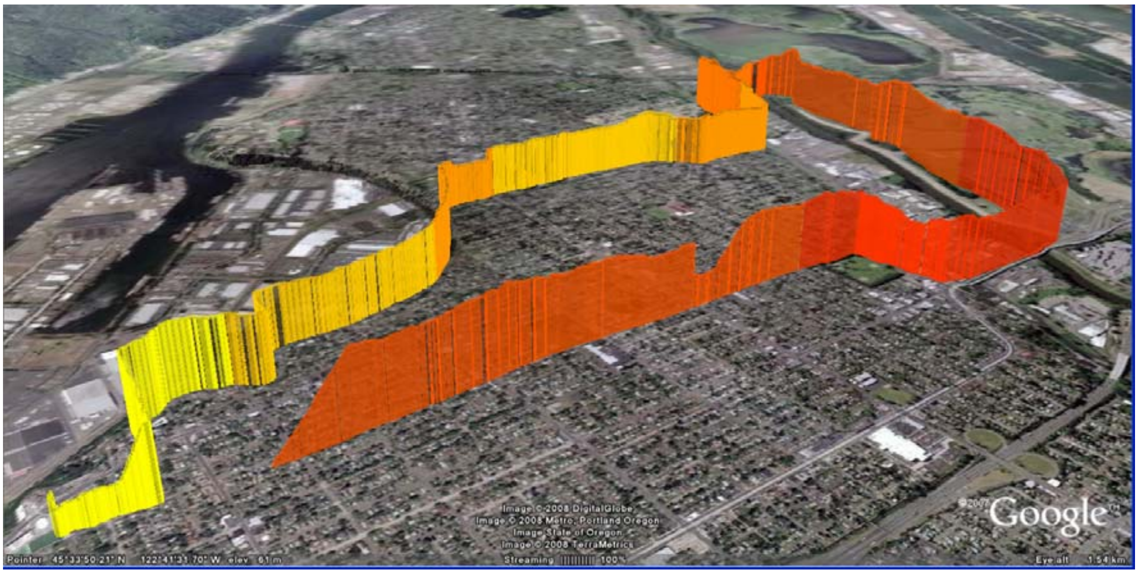

Figure 5. Visualization of running speed for a 1 hour example run in Portland, Oregon, USA. The image is based on Google Earth. The speed is displayed as the height of the colored band along the running track. The self-rated fatigue state is color coded. Yellow means little or no perceived fatigue. The redder the band becomes, the higher is the perceived fatigue state of the athlete.

Conclusion and further work

We designed and realized a system for collecting real-time subjective, physiological and other information about a sports session. For the implementation we made use of the advanced computational power and the multimedia capabilities of mobile phones, which offer a high adaptability through software packages tailored to the problem at hand. Our system is capable of asking questions about the subjective state of an athlete as defined in a configuration file or as a reaction to external events. Other information like speed and position can be collected via an internal or external GPS receiver. It is also possible to connect other sensors like heart rate monitors using Bluetooth connection.

The system has already proven its usability in practice. The system has been found to be not hindering to the sports activity of running by a majority of 84 athletes. Run information has been collected for an hour for each of the athletes with 100% reliability for the audio information and 99.93% reliability for the position information. The position and other information can very conveniently be visualized using Google Earth. The data of this ongoing study is currently analyzed, the results will be the topic of another presentation.

Our system could also be used for evaluation of other outdoor and endurance sports like rowing, cross-country skiing and biking. It is highly mobile, lightweight and applicable even for long studies due to extendable memory and high battery capacities. To our knowledge, it is the first time that a surveying system has been implemented on a mobile phone.

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Self-Organizing Maps as a Tool to Analyze Movement Variability

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Abstract

Self-Organizing Maps possess unique properties that remove redundancies in a high-dimensional input space and map that input space to a low dimensional output space, thereby showing non-linear relationships in the input data. This ability makes Self-Organizing Maps attractive for measuring inter-limb coordination patterns. The current study takes previously published data (Bartlett, Bussey, & Flyger, 2006) used to compare the reliability of different operators digitizing gait patterns with and without anatomical markers. The trained network was simulated and analyzed qualitatively using the trajectory of activated nodes for each input vector, similar to Barton, Lees, Lisboa, & Attfield (2006). Qualitative differences in map trajectories were seen between Marker and No-Marker conditions and supported the results of the original publication that, when using 2-D videography, manually digitized markers allowed accurate estimation of movement variability, whereas the No-Marker condition did not. This finding is shown by the No-Marker trajectory travelling further from the center of the network cluster than the Marker condition. Additionally, the map trajectories revealed that changes in coordination at different phases of the movement can be identified. For most trials the Marker trajectory travels closer to the centre of the map than the No-Marker condition which, as is explained by the neighbourhood function, indicates less variability. The consistency between conventional biomechanical analysis techniques and the qualitative assessment of Self-Organizing Map outputs adds to the validity of the Self-Organizing Map as an accurate measurement tool for coordination. The ability to identify changes in coordination using the map trajectories illustrates the potential for the Self-Organizing Map to show novel information about the coordination pattern.

KEYWORDS, ARTIFICIAL NEURAL NETWORKS, COORDINATION, RELIABILITY, SELF-ORGANIZING MAPS, VARIABILITY

Introduction

From dynamical systems theory, human behaviour is thought to be non-linear and self-organizing (Davids, Glazier, Araujo, & Bartlett, 2003; Kelso, 1995). Using non-linear analyses may help identify characteristics in the movement pattern that would otherwise go unnoticed. Artificial neural networks are non-linear and thus conform to the dynamical systems theoretical framework. By analyzing human movement data with artificial neural networks, the data is not forced through a linear path, as is the case with most statistical operations. This analysis technique is intended to reduce the dimensionality of the data so it can be visualized while preserving the original topology of the data.

The Kohonen Self-Organizing Map is an artificial neural network designed for pattern classification through dimensionality reduction. The Self-Organizing Map can be thought of as a layer of nodes with associated weight vectors, fed forward by a layer of inputs. Each input node is connected to all output nodes (see Figure 1). The weight vectors of the nodes in the output layer are the same dimensionality as the input. Through an iterative process the network strives to map a low dimensional representation of the input while preserving the topology of the data.

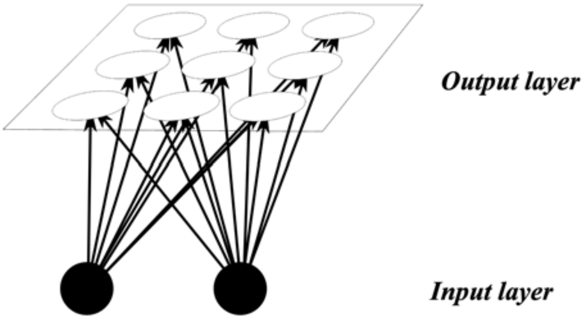

Figure 1. The connections between input and output layers.

The Self-Organizing Map uses an unsupervised learning strategy to update the weight vectors of the output nodes in an effort to match the input more closely. Weights are updated if the weight vector has the smallest Euclidean distance to the input. Euclidean distance is defined by

$$d_i = \sqrt{\sum_{i=1}^{n} (V_i - W_{ni})^2} \tag{1}$$

where V_i is the i^{th} input vector and W_{ni} is the i^{th} weight vector and the n^{th} node on the topological map. The output node, W_{ni}, whose weight vector has the smallest Euclidean distance of all nodes is declared the best matching unit and has its weights updated by the learning constant and neighbourhood function, given by

$$W_{i+1} = W_i + \psi_t \alpha_t (V_i - W_{ni}) \tag{2}$$

where α_t is the learning rate at iteration t and lies between 0 and 1 and ψ_t is the neighbourhood function at iteration t. Nodes in the output layer are updated based on their proximity to the best matching unit. Nodes located more closely to the best matching unit are updated more, relative to nodes that are further from the best matching unit - but still in its neighbourhood. Nodes in the best matching unit's neighbourhood are thus influenced by that input using the neighbourhood function.

In this study, default values from the SOM toolbox (for MATLAB) for the learning parameters were used (Vesanto, Himberg, Alhoniemi, & Parkankangas, 2000). An important note about the learning parameters is that they start with fairly large values and decay towards zero as t increases. A high initial neighbourhood radius ensures that the map spreads globally. If the radius is set too small in the initial stages, groups of data may get clustered together without having the chance for other similar inputs to enter the neighbourhood, this would result in an assortment of separated clusters not representative of the input distribution.

In a network not larger than a few hundred nodes, specifying the learning parameters (learning rate and neighbourhood function) is not crucial. It is generally accepted that initial values for the neighbourhood size be approximately one fifth to half the size of the network and the learning rate should begin roughly between 0.9 and 0.5. Variations within these ranges will not drastically affect a small network (Kohonen, 2001).

In the engineering domain, Self-Organizing Maps are often used for pattern classification applications using discrete variables (i.e. images (Hussain & Eakins, 2007), geographical regions (Ong & Abidi, 1999) and structural biological features (Hyvönen et al., 2001)). There are of course patterns that the human brain can recognize that artificial neural networks have not been able to. Yet there are also high dimensional patterns that have been recognized by artificial neural networks and not the human brain, illustrating the potential use of this method. With movement data, similar trials would be grouped into topologically similar regions on the output map. However, some researchers of human movement (i.e. clinicians, biomechanists) are more interested in classifying phases, or components, of a movement using continuous data. To accomplish this, individual time frames taken from each movement trial are used as input instead of the whole data set. This is to allow similar phases of the movement to be clustered together. An analysis of the clusters allows the researcher a glimpse of the coordination states during the movement.

A useful property of the Self-Organizing Map is the option to simulate the network with a portion of the training data. By doing so, the best matching units for all input vectors of one scoring of a trial can be traced on the trained network. Simulating the network allows the researcher to compare different trials or groups of trials. Comparing the best matching units of different trials at the same time frame can offer unique information about the difference in coordination states between the trials used for simulation. For this study a trajectory of best matching units throughout the time series was used to compare between and within conditions of the data set.

This study uses data from Bartlett, Bussey, & Flyger (2006) to a) validate Self-Organizing Maps as a tool for biomechanical analysis, b) show that Self-Organizing Maps provide the capability for something novel to be learnt about the data that cannot be realized using analyses of variance, and c) critique a new visualization technique for the Self-Organizing Map.

Methods

The Dataset

The data used for this study were adopted from Bartlett et al. (2006). One runner was filmed running on a motorized treadmill at 16 km/h for ten separate trials, two-dimensional videography captured movement in the sagittal plane at 50 Hz. In five of the ten trials the runner did not wear anatomical markers while in the other five trials he wore reflective markers on the right shoulder, elbow, wrist, greater trochanter, knee, lateral malleolus and the fifth metatarsal head. All trials were filtered using a fourth order Butterworth filter with a cut-off frequency set to 6 Hz based on residual analysis.

From each trial, three consecutive strides were chosen to be digitized. Four trained operators digitized all trials for one condition on alternate days to establish inter-operator reliability. The No-Marker condition trials were digitized before the Marker condition trials to prevent the operators from learning the marker positions. To establish intra-operator reliability, this process was repeated for five days. The data were time normalized to 100 frames so phases of the gait cycle could be described as a percentage of the gait cycle. The filtered coordinates of the above mentioned anatomical landmarks were used to create joint angles which were used as input for the network.

Training the Network

a) Creating the Input Vector

Three time samples at constant intervals of 5% were appended to create data triplets (see Figure 2). These data triplets were used to represent the temporal nature of the pattern of the data to the network (Barton et al., 2006). Time samples are organized as rows in the SOM toolbox, new rows were created as,

([Time = 1%], [Time = 6%], [Time = 11%])
([Time = 2%], [Time = 7%], [Time = 12%])
([Time = 3%], [Time = 8%], [Time = 13%])
. . .
. . .
([Time = 90%], [Time = 95%], [Time = 100%]).

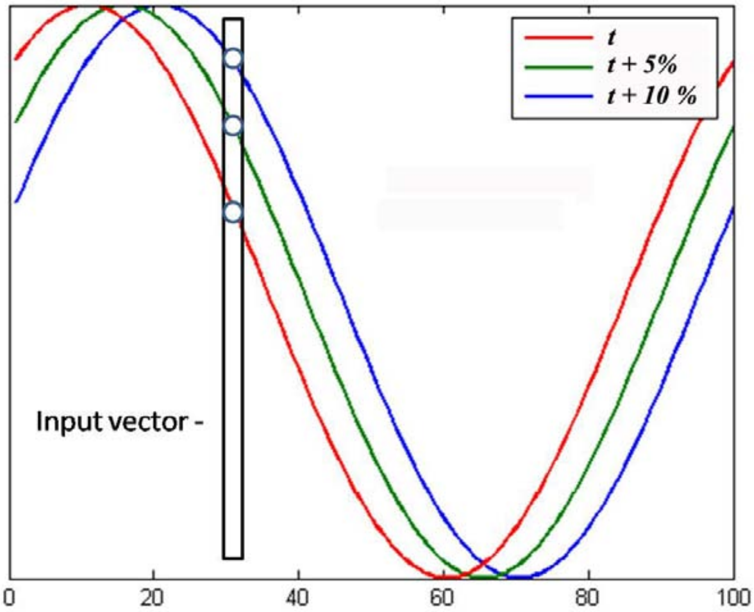

Figure 2. Example of time shifted at constant interval to represent the temporal nature of the pattern of the data.

The necessity for there to be ten samples in the trial following the first sample in the triplet reduced the number of input vectors per trial from 100 to 90. With four operators digitizing five trials in two conditions, on five different days the network was trained with 200 trials (20 scorings of each trial). Each trial consisted of 15 input variables (5 x 3 data triplets) and 90 time samples resulting in 270,000 data points in the dataset.

b) Initialization

Before initializing the map, the eigenvalues and corresponding eigenvectors of the training data are calculated to determine the map size. Once the number of map units is known the dimensions of the map are calculated. The ratio of the two largest eigenvalues, λ_1 and λ_2 respectively, is used to determine the dimensions of the map.

$$\frac{n}{m}=\sqrt{\frac{\lambda_1}{\lambda_2}} \tag{3}$$

For the dataset used in this study the map size was a [29, 23] hexagonal lattice. Linear initialization, which organizes the weights of the nodes linearly along the two (number of dimensions of the map) largest eigenvectors of the training data, was used to speed up training (Vesanto et al., 2000).

c) Training

In batch training, Euclidean distances to all nodes for each input vector are calculated. Instead of calculating the distances as in equation (1), the process is accelerated by expressing the learning algorithm as a matrix operation (Vesanto et al., 2000). As a result of redundancies in the data, an efficient initialization process and the batch training algorithm, the network was able to model this data set extremely quickly.

d) Visualization

Much research has been focused on visualization techniques for the low dimensional map outputs (Kohonen, 2001; Pampalk, Rauber, & Merkl, 2002; Pölzlbauer, Rauber, & Dittenbach, 2005). To show the coordination state at a given time frame, the map can be arranged into a fixed grid (grid space) with the best matching unit highlighted. Similarly, a trajectory can be added on top of the grid to show several consecutive coordination states throughout the trial (Barton, 1999; Barton et al., 2006; Bauer & Schöllhorn, 1997; Lees & Barton, 2005; Schöllhorn & Bauer, 1998). The grid trajectory is an advantageous visualization technique because qualitative changes in coordination are easily seen. Different best matching unit trajectories between trials allow for generalizations to be made about the movement, not only that there is a qualitative change in coordination, but at which phase of the movement the qualitative change occurs.

This study uses a unified distance matrix (u-matrix) for visualization of the trained network and the best matching unit trajectory. Each ‘unit’ in the u-matrix will be referred to as a cell for clarity, so that it is not confused with nodes in the output layer. Recall that each output node in the SOM has an associated weight vector. The u-matrix represents each output node (grid space) as an uncoloured (white) cell. Between each pair of nodes / white cells is a coloured cell, which represents the similarity of the weight vectors of that pair of nodes. Blue represents a pair of weight vectors which are close (in the input / weight space), red represents vectors which are far apart. Hence for each pair of adjacent nodes in the output layer we also have a coloured cell representing how similar the weight vectors of those two nodes are. This makes the u- matrix a hybrid representation of grid space and weight space (see Figure 3).

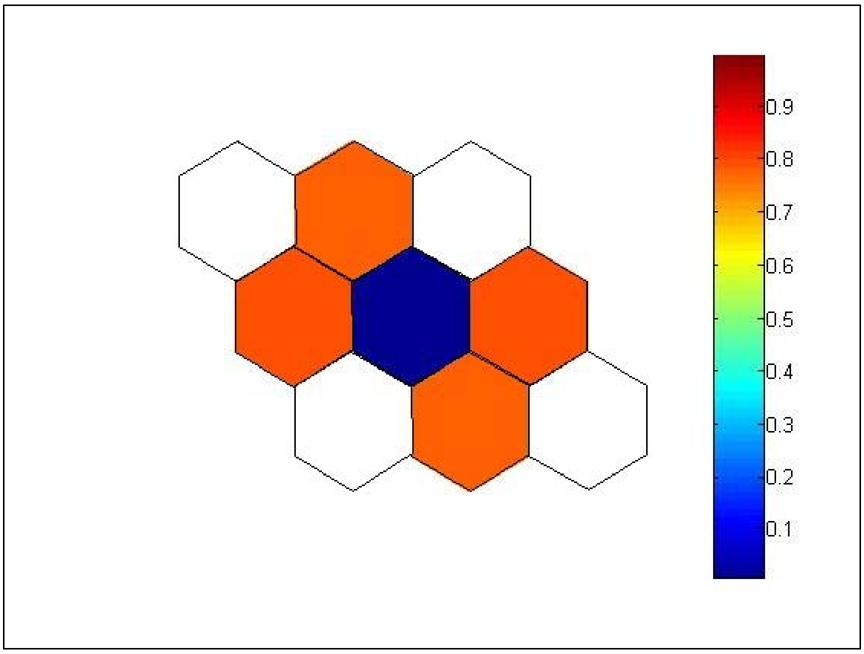

Figure 3: A 2X2 u-matrix. The colourless cells in the u-matrix represent nodes in the output layer. The distance between adjacent cells is represented by coloured distance cells. The blue distance cell represents similar weights of the neighbouring cells.

For a 'sheet' map topology of size [m n], the corresponding u-matrix would be of size [2m-1 2n-1]. Nodes which are adjacent in the output layer (grid space) are represented by cells which are adjacent in the u-matrix. The u- matrix, however, represents the proximity of the weight vectors of each pair of adjacent nodes with coloured distance cells. The coordinates of the nodes are much like a rectangular grid; however, for the hexagon-shaped cells to fit, every other row in the grid in shifted horizontally by half a unit. Visualizing the best matching unit trajectory in weight space is an important distinction to make because it allows for a more objective assessment of the change in coordination between trials.

Analysis

The trajectory of the best matching unit sequence through the time series of the trial was used to compare various trials simulated on the same trained network (Barton, 1999; Barton et al., 2006; Bauer & Schöllhorn, 1997; Lees & Barton, 2005; Perl, 2004; Schöllhorn & Bauer, 1998). The trajectories used for this study are in both grid space and weight space, implying that the distances between cells actually represent the difference between the weight vectors. Thus, the comparison of the best matching units between trials at the same time frame represents the similarity (or dissimilarity) of the movement pattern during that coordination state.

The Self-Organizing Map excels in clustering similar input vectors. On the u-matrix, clusters (blue distance cells) and borders (more brightly coloured distance cells) can be identified. The blue distance cells represent a small Euclidean distance between neighbouring weight vectors and thus are representative of clusters of similar input vectors. If there is more than one cluster in the output layer those clusters will be separated by more brightly coloured distance cells (see Figure 4), indicative of a larger Euclidean distance between the weight vectors and less similarity in the input distribution. Shifts between best matching units within clusters do not indicate a major change in coordination; however, conclusions about the variability of the dataset can be made. If the path of the best matching unit trajectory is inconsistent between cycles of the same trial there may be high inter-cycle variability and if the trajectory between trials is inconsistent there may be high inter-trial variability. Additionally, for the data set used in this analysis, differences between trajectories of different scorings of a trial by the same operator may be indicative of intra-operator variability whereas differences between trajectories of all scorings of all trials in each condition could indicate intra-condition variability, which is the focus of this study.

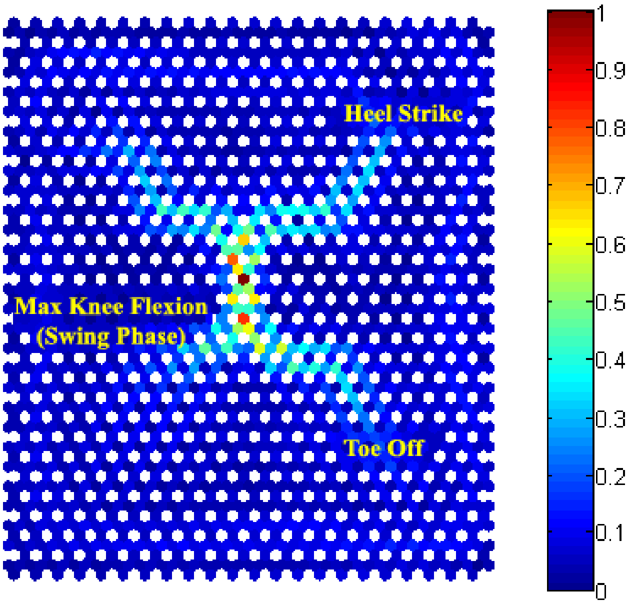

Figure 4. Phases of gait cycle visualized on u-matrix

To quantify the difference in the best matching unit trajectories between all scorings of each trial the Euclidean distance between all scorings for each data triplet was summed to give a measure of similarity within each trial. This analysis technique is used to further validate visual analysis of best matching unit trajectories.

An equally important consideration when analyzing the map trajectories is how well the best matching units on the output map represent the input. Quantization error is a measure of the fit of the map to the input distribution in the form of an average distance between each input vector and its best matching unit. Quantization error between several different elements can be found. In this paper an average quantization error between the input and weight vectors of individual trials was used to characterize the variability between Marker and No-Marker conditions.

Results and Discussion

The purpose of this study was to a) replicate the findings of Bartlett et al. (2006), b) show something novel as a result of using Self-Organizing Maps and, c) critique a new visualization technique for Self-Organizing Maps.

Bartlett et al. (2006) concluded that movement variability accounted for more of the total variability in trials that were digitized with anatomical markers compared to trials digitized without anatomical markers. In the No-Marker condition, inter-operator variability for the ankle was five times higher than the movement variability while the hip was twice as high as the movement variability. Movement variability contributed to a particularly low proportion of the total variability in the No-Marker condition for all operators digitizing the ankle and the hip. None of the operators achieved movement variability accounting for more than 25% of the total variability for ankle angle and for two out of four operators, movement variability did not account for more than 50% of total variability for hip angle. The physical errors contributing to these differences are not the same for each condition. In the Marker condition, the operator had to ascertain the centroid of a circular physical marker centred over the joint axis of rotation. This error could have been of a similar magnitude to the resolution of the image. In the No-Marker condition, the operator had to estimate the position of the joint axis of rotation without any marker to assist; in this condition, the error in so doing was, not surprisingly, much larger than the screen resolution. From this, the authors suggested that multiple operators not be used as they would add an extra source of variability; and that anatomical markers should be used when capturing 2-D videographical data for the purpose of assessing movement variability.

Upon visualizing the trained network with the u-matrix, a brightly coloured, centrally located, branching border can be seen that separates clusters of cells identified by blue distance cells. By matching the time frame of the best matching unit it was found that certain phases in the gait cycle could be identified in the u-matrix. Distinct phases identified on the u-matrix were the contact phase and swing phase (see Figure 4). The contact phase is shown between heel strike and toe off while the swing phase took up the remainder of the u-matrix.

A qualitative difference between trials of the Marker and No-Marker conditions is apparent by visual analysis. In the Marker condition the best matching unit trajectory travels closer to the brightly coloured border than the trajectory for the No-Marker condition. As a result of linear initialization the weights of the nodes are spread uniformly throughout the input data. Nodes along the edges of the map represent extreme values in the data while nodes located more closely to the centre represent more typical data. Trajectories passing more closely to the centre of the u-matrix may occupy more typical coordination patterns compared to other coordination patterns in the dataset.

Visualizing the trained network on a u-matrix allows the visualization to be in grid/weight space and thus differences between best matching units for various trials can be found using Euclidean distances between the weights. To show similarity or dissimilarity within trials of the same marker condition the Euclidean distance between all scorings of each trial is shown in Table 1. The Euclidean distances between all trials in the Marker condition is less than the Euclidean distances between all trials in the No-Marker condition. Trials one and two in the No-Marker condition show smaller Euclidean distances than the remaining trials in the No-Marker condition – although still larger than for the Marker condition trials. The difference between Euclidean distances for each condition shows that the best matching unit trajectories in the Marker condition, for each trial, are more consistent than the trajectories in the No-Marker condition. The higher Euclidean distances between all scorings of trial three, four and five of the No-Marker condition compared to the other two trials is a unique finding that was not exposed in the original study using analyses of variance. The original analysis made comparisons based on each individual angle while this study compares trials based on a composition of all angles. Grouping the variables by means of the Self-Organizing Map shows that the coordination of the variables in trials three, four and five is more variable than the other two trials in the No-Marker condition. The differences shown in Table 1 indicate that digitizing participants who are wearing anatomical joint markers increases the reliability of the procedure. This analysis is intended to provide more objectivity to the qualitative difference between trajectories.

Table 1. Euclidean distances between all 20 scorings of each trial

Marker Condition					
Euclidean Distance	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	22.9	23.7	21.4	29.1	33.9

No-Marker Condition					
Euclidean Distance	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	46.7	49.2	96.9	74.7	94.8

Upon analysis of the quantization errors, the mean error for the Marker condition (0.063±0.007) was significantly less than the mean error for the No-Marker condition (0.108±0.018), $p < .001$ (see Figure 5). The outside edges of the u-matrix represent the extreme values in the weights of the nodes and should, therefore, be activated less often than the more typical nodes located closer to the centre. The largest proportion of total quantization error was contributed by the weights of nodes located along the edges of the u-matrix.

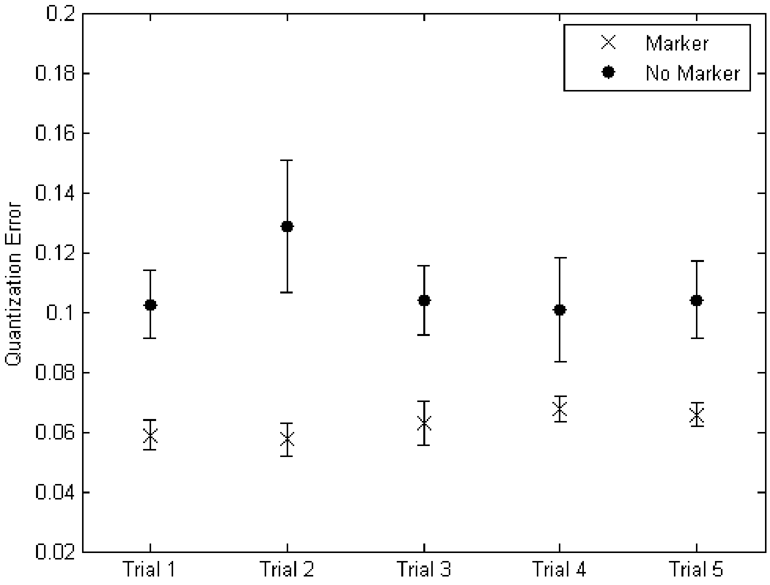

Figure 5. Mean (± SD) quantization errors for all scorings of each trial.

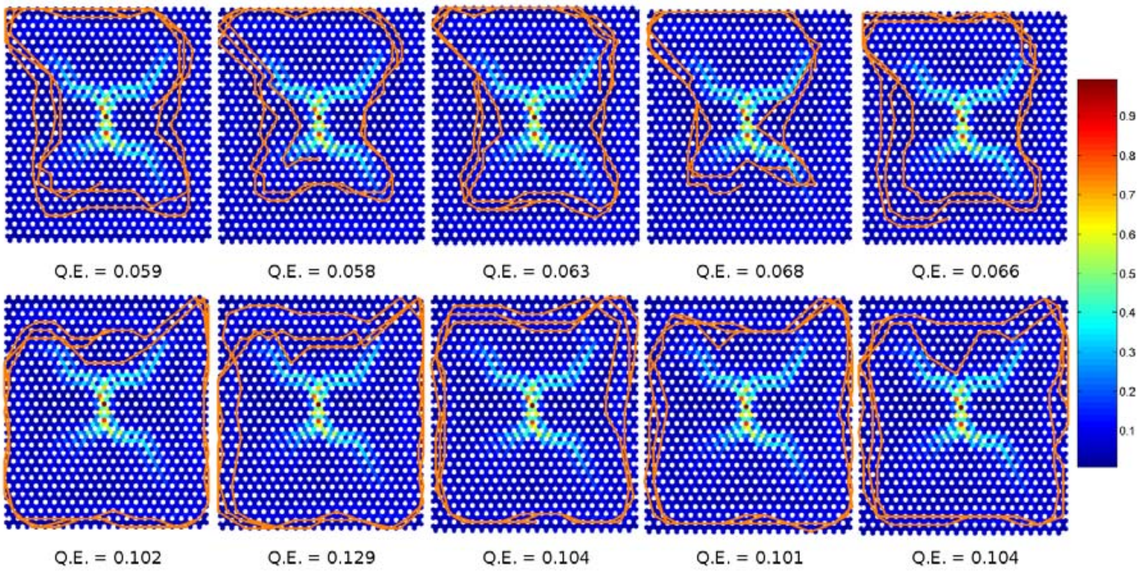

Figure 6. Best matching unit trajectories for trials (1 to 5 from left to right) digitized on the fourth day by the same operator in the Marker condition (top row) and in the No-Marker condition (bottom row). The best matching unit trajectory is shown by the orange line. Mean quantization error for all scorings of each trial is shown below each respective trial.

As shown in Figure 6, the No-Marker condition trajectories travelled on or close to the edges of the u-matrix for three out of four edges on the map. From this the No-Marker condition trials can be thought of as more variable because the quantization error for each input and its best matching unit was higher than in the Marker condition. The lower quantization error in the Marker condition does not mean the trials or the cycles within the trials are less variable; rather, the scorings of these trials is less variable on a trial by trial basis.

Using Self-Organizing Maps to analyze human movement is more complicated than conventional statistical approaches; therefore, for Self-Organizing Maps to be appropriate they must not only be shown to be valid but must also have the potential to highlight something new in the data. The original publication relied on comparisons between individual angles, angular velocities or angular accelerations to establish the reliability of digitizing a participant running on a treadmill in Marker and No-Marker conditions. In the current study the analysis of best matching unit trajectories as well as quantization errors supported the original findings and also may have uncovered something new in the data. The best matching unit trajectories in the Marker condition travelled closer to the centre of the u-matrix along three of the four sides of the map while the No-Marker trajectory travelled closer to the centre along the top edge of the map. The top edge represents the phase in the gait cycle when the knee is extending for heel strike. A speculative reason for this could be that as the heel strikes the running surface the foot moves in the shoe slightly, meaning that the marker on fifth metatarsal may not be accurately representing the motion of that anatomical landmark. This is however only speculation, because of the redundancy in the data, the differences in the data are very small and difficult to give definitive meaning to.

Conclusion

This study supports other studies that show Self-Organizing Maps to be effective for classifying movement patterns using time series data (Barton, 1999; Barton et al., 2006; Bauer & Schöllhorn, 1997; Lees & Barton, 2005; Schöllhorn & Bauer, 1998). Output from the Self-Organizing Maps also supported the findings of the original publication (Bartlett et al., 2006) using analyses of variance. The distance cells in the u-matrix allow for meaningful conclusions to be made about the shifts of coordination state as the Euclidean distance between the cells in the u-matrix are representative of the difference between the weight vectors of the respective nodes. The potential for quantifying the differences between movement patterns based on their map trajectories lies in using a visualization technique, such as the u-matrix, that incorporates information about weight space.

Caution must be used with artificial neural networks. The network output must be analyzed before any inferences about the underlying movement can be made; however, observations made in this study are consistent with expectations based on the nature of Self-Organizing Maps. In this study Self-Organizing Maps were shown to be effective in distinguishing between the two digitizing conditions. Since human movement data is inherently redundant an effective method for reducing the redundancies in the dataset holds great potential for movement analysis. Various unique properties of Self-Organizing Maps make them attractive for studying human movement and also make them conform with the dynamical systems theoretical framework. Further work needs to be done to make more concrete statements about the underlying coordination pattern based on best matching unit trajectories.

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Mechanical and Mathematical Modeling of Sport Archery Arrow Ballistics

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Abstract

Mechanical and mathematical model of external ballistics of the modern sport bow has been proposed. The force of air drag, shear friction, and drag on the fletching, and the additional force that depends on the angle of attack have been taken into account in the model. The corresponding Cauchy problem was stated and solved using the Runge-Kutta method and the program NDSolve from the software packet Mathematica 5. The model was applied to the example of the modern sport bow and arrow within the framework of the International Archery Federation Standard. Quantitative dependencies of kinematic parameters of arrow ballistics were obtained as a function of bow and arrow system adjustment. As a result of computer simulation based on the model, estimates were calculated for the difference in the vertical coordinate of the arrow tip on a target for the Olympic distance (70 m) caused by the initial angle of attack and initial angular velocity.

KEY WORDS: ARCHERY, BALLISTICS, MECHANICAL AND MATHEMATICAL MODELING

Introduction

External ballistics of the archery arrow (Appendix 1) were previously investigated using a model of particles and methods of theoretical mechanics both with (Tapley, 1999) and without air drag (Funk, 1968). The force of the drag was estimated as the squared speed of an arrow and formulated as the sum of two components: the force of the bar shaft and the force of the fletching. Marlow (1981) presented results of aerodynamic research oncylindrical arrows and collected empirical coefficients for calculation of the air drag force components. In recent years, we made some attempt on the issue and developed a model of the arrow as a shaft eliminating air drag during a flight (Zanevskyy, 1999; 2000; 2001; 2002; 2004).

This research aims to study external ballistics of the archery arrow using an aerodynamic model of a stiff cylindrical shaft with a pointed tip and a fletched tail.

Methods

Methods of theoretical mechanics (d’Alembert principle, aerodynamics models), mathematics (Cauchy problem, Runge-Kutta method), and computing (Mathematica software packet, computer simulation) were used as the basis for the research.

To analyze the external ballistics of an arrow as a long shaft, we need to take into consideration the arrow orientation relative to the direction of arrow flight and the air drag as a function of the angle of attack. Research on the issue has been provided regarding tactical missile aerodynamics at subsonic speeds (Hemsch & Nielsen, 1986).

In the well known studies on archery arrow ballistics (Balov, 1975; Tapley, 1999), an air drag force was virtually divided into a three components: the force of front air drag, shear friction on the cylindrical surface of the shaft, and drag on the fletching. Unfortunately, there are no standard methods for air drag modeling of an arrow in free flight: different mathematical equations have been used, which results in different values for air drag force.

The model of air drag for a small angle of attack estimates a constant by a magnitude and direction component of a drag force (the same as for zero angle of attack) plus a normal to the axis of missile with a magnitude proportional to squared value of the angle of attack (Hemsch & Nielsen, 1986). We can borrow the corresponding coefficient of aerodynamic drag force for the additional component (0.63) from known research on the aerodynamics of short cylindrical circled missiles in air flow normal to the axis of cylinder (under the condition of approximately equal diameter and length of cylinder) (Koshkin, 1991). The other approximations of the model are: elimination of captured to the arrow air mass; no effect of the arrow rotation on the drag; bending oscillations of the arrow are negligibly small.

The complete mathematical model of an air drag consists the following equations:

$$F_1 = k_1 V_C^2;\; F_2 = k_2 V_C^2;\; F_3 = k_3 V_C^2;\; F_4 = k_4 \alpha^2 V_C^2, \tag{1}$$

where $F_1,\ F_2,\ F_3,\ F_4$ are the components of the air drag force corresponding to the front drag, shear friction on the cylindrical surface of a shaft, drag on the fletching, and the additional force depended on the angle of attack, respectively (Figure 1); $k_1,\ k_2,\ k_3,\ k_4$ are the corresponding coefficients of air drag; V_C is the speed of center of mass of the arrow ($V_C^2 = x_C'^2 + y_C'^2$). The Cartesian coordinate system xOy is fastening to the vertical plane of shooting with the origin on the line of shooting. The force vectors $\vec{F}_1,\ \vec{F}_2,\ \vec{F}_3$ are orientated opposite to the vector of velocity $\vec{V}_C$, i.e. along the airflow, and the force vector $\vec{F}_4$ is normal to the arrow axis.

The aerodynamics of long cylindrical bodies with cone-like tips have been studied in detail for missile flight. It is known that during the flight of a long missile at subsonic speed, the front drag force is approximately five times smaller than the shear friction force, as the height of cone (l_1) is approximately three times longer than the diameter (d) of the cylinder (Hemsch & Nielsen, 1986). A modern sport archery arrow has parameters of $l/d > 20$, where l is the arrow length. Therefore, we can assume: $F_1 / F_2 \approx 5$, where $F_2 = fl$ is the resultant force of shear friction (see Figure 1a). Here, we assume constant distribution of the shear drag force on the cylindrical surface, i.e. the resultant force locatated in the middle of the arrow (point M).

There are no known publications on the problem of air drag dependent on the angle of attack of the arrow. Bow and arrow adjustment means, among other requirements, an optimal angle of attack of the arrow at the instant that the arrow launches from the string. The problem needs much effort and time, because the archer solves it using empirical methods of attempts and mistakes (Bajer *et al.*, 1996).

We modelled the additional component of the air drag force using equation $F_4 = C_\alpha S q \alpha^n$, where C_α is a coefficient of air drag; S is the cross-sectional area of the arrow normal to the airflow; $q = \frac{1}{2}\rho V^2$ is the velocity pressure; ρ is air density; n is a power coefficient that is equal 2 in the case of subsonic speeds (see Figure 1b).

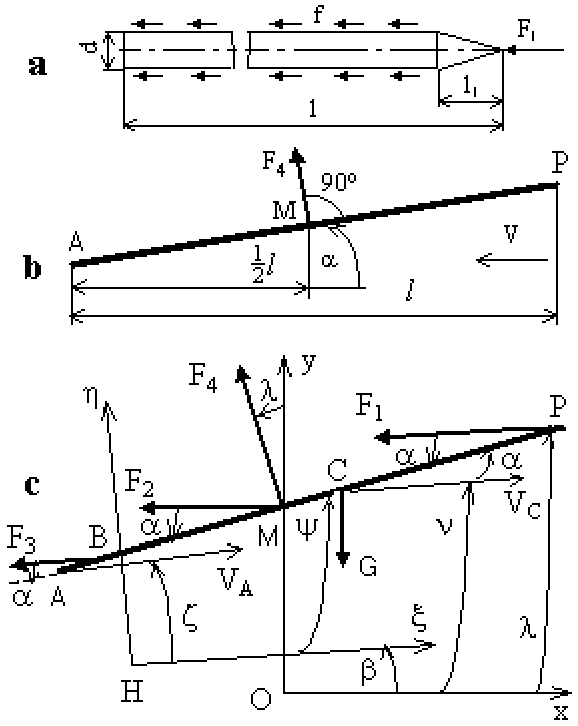

Figure 1. Forces acting an arrow: **a** – Scheme of aerodynamic drag during the projectile motion of the un-fletched arrow with zero angle of attack (F_1 is the front drag force; f is the force of air friction distributed on the cylindrical surface of the shaft); **b** – Scheme of additional drag depended of the angle of attack α (*A* and *P* are arrow ends); **c** – Scheme of forces acting an arrow during the free flight (*C* is the arrow center of mass; *B* is center of drag on the fletching; *M* is center of shear friction on the cylindrical surface of a shaft; G is the arrow gravity force).

Assigning the coordinates of center of mass of the arrow (x_C, y_C) and the attitude angle of the arrow λ as generated coordinates and using d'Alembert principle, we get equations of the air aerodynamics in free flight. The first equation describes the sum of projections of all the forces acting on the arrow in the horizontal axis, the second is the same in the vertical axis, and the third one is the sum of the force moments relative to the center of mass of the arrow:

$$m_a x_C'' + \left[(k_1+k_2+k_3)\cos\nu + k_4\alpha|\alpha|\sin\lambda\right]V_C^2 = 0;$$

$$m_a(y_C'' + g) + \left[(k_1+k_2+k_3)\sin\nu - k_4\alpha|\alpha|\cos\lambda\right]V_C^2 = 0;$$

$$I_C\lambda'' + \begin{bmatrix} -k_1(0.5-\varepsilon) + k_2\varepsilon + \\ k_3(0.5+\varepsilon-\phi) + k_4\varepsilon|\alpha| \end{bmatrix}\alpha l V_C^2 = 0, \qquad (2)$$

where $m_a = m_p + m + m_f$ is thetotal mass of the arrow and its components (corresponding to the mass of the head, the shaft, and the fletching); I_C is the moment of inertia of the arrow relative to its center of mass; $\varepsilon = \frac{e}{l}$; $e \equiv \overline{MC}$ is the distance from the middle of the arrow to the center of mass (see Figure 1b); $\phi = \frac{f}{l}$; $f \equiv \overline{AB}$ is the distance from the tail to the center of air pressure; $\nu,\ \alpha,\ \lambda$ are correspond to the projection angle, the angle of attack, and the attitude angle of the arrow; g is gravitation constant; the sign $(')$ means derivation of time.

Because the magnitude of the angle of attack in sport archery is a small value (not bigger 0.02 rad) (Zanevskyy, 2006), we can assume in eqs. (2): $\sin\alpha \approx \alpha; \cos\alpha \approx 1$.

The initial conditions (at the instant as the arrow launches from the string) are:

$$t = 0\,,\, x_C(0) = x_C^*; y_C(0) = y_C^*;\ \lambda(0) = \psi(0) + \beta; \lambda'(0) = \psi'(0);$$
$$x_C'(0) = \xi_C'(0)\cos\beta - \eta_C'(0)\sin\beta;\ y_C'(0) = \eta_C'(0)\cos\beta + \xi_C'(0)\sin\beta \tag{3}$$

where ξ_C, η_C are the coordinates of the center of mass of the arrow (in the Cartesian coordinate system $\xi H\eta$ with longitudinal axis of a bow handle as $H\eta$ at the instant when the arrow launches from the string); ψ is the attitude angle of the arrow relative to the axis $H\xi$; β is the angle of attitude of the bow. In the eqs. (2) and (3), kinematic parameters correspond with the equations below:

$$\nu = arctg\frac{y_C'}{x_C'};\ \alpha = \lambda - \nu;\ V_A^2 = \xi_A'^2 + \eta_A'^2. \tag{4}$$

Additionally, we account in the initial conditions (3) equations, which describe correlation between speed of the tail and the center of mass of the arrow.

$$\begin{aligned} \xi_C'(0) &= \xi_A'(0) + \psi'(0)l(0{,}5+\varepsilon)\sin\psi(0); \\ \eta_C'(0) &= \eta_A'(0) + \psi'(0)l(0{,}5+\varepsilon)\cos\psi(0) \end{aligned}. \tag{5}$$

The position of the arrow's center of mass along its longitudinal axis corresponds with the distance, discipline of shooting, and arrow type. The quantity coefficient that describes the relative distance from the middle of the arrow to its center of mass is equal for modern sport arrows $\varepsilon = 7 - 11\%$.This coefficient, along with arrow mass and stiffness, are the three main characteristics of arrows. The arrow's center of mass can be displaced with different masses of arrowheads. Assuming the centers of mass and drag of the fletching at the same point, we wrote expressions for the arrowhead mass and of the moment of inertia of the arrow (see Figure 1c):

$$m_p = \frac{m_{sh}\varepsilon + m_f(0{,}5+\varepsilon-\phi)}{0{,}5-\varepsilon};$$
$$I_C = \left[m_p(0{,}5-\varepsilon)^2 + m_{sh}\varepsilon^2 + m_f(0{,}5+\varepsilon-\phi)^2\right]l^2 \tag{6}$$

According to the rules of the International Archery Federation (FITA), the distance of shooting is between the line of shooting and a point projected from the target center to the ground (Figure 2). The center of a target is situated at a height of approximately $0.9 \div 1.0$ m. The target has a slope with an angle δ of its plane to the vertical. The vertical coordinate of the arrow tip at the instant of its contact with the target that means a competition result is described with expression below:

$$y_P = y_C + \frac{(0{,}5-\varepsilon)\lambda l}{\cos\delta} \tag{7}$$

The system of differential equations (2), initial conditions (3) together with the algebraic equations (4)–(7) are a mathematic model of external ballistics of an arrow, and this is needed to solve the Cauchy problem. Because there are transcendent functions and non-linear components regarding the derivations in the differential equations, it is impossible to get analytical solutions of the problem. Therefore, we used Runge-Kutta method applied in the program NDSolve from the packet Mathematica 5. The text of the software program is presented in the Appendix 2.

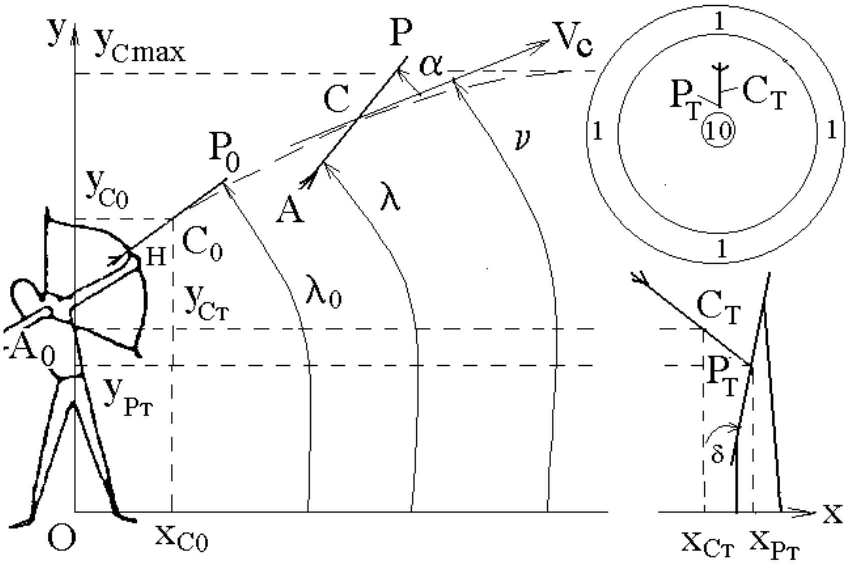

Figure 2. General scheme of shooting (view in the vertical plane): subdivides “$_0$” and “$_T$” mark parameters corresponding to the instant the arrow launches from the string and as it touches a target.

Results and discussion

The model and the methods of its study have been tested on an example of the modern sport bow and arrow with parameters of a shot below: $m_a = 0{,}025\,\text{kg}$; $l = 0{,}7\,\text{m}$; $\varepsilon = 0{,}09$; $\phi = 0.05$; $I_C = 1.286\cdot 10^{-3}\,\text{kgm}^2$; $k_1 = 1.698\cdot 10^{-5}$ kg/m; $k_2 = 0.339\cdot 10^{-5}$ kg/m; $k_3 = 3.306\cdot 10^{-5}$ kg/m; $k_4 = 2.247\cdot 10^{-3}$ kg/m; $V_C = 52.8$ m/s; $\beta = 0.125$; $\delta = 10^\circ$; $g = 9.81$ m/s^2; $x_C^* = 0.906$ m; $y_C^* = 1.632$ m; $\alpha(0) = -0.01 \div 0.01$; $\lambda'(0) = -0.1 \div 0.1$.

Kinematic parameters of arrow ballistics with zero initial angle of attack and zero angular velocity of the arrow in the vertical plane are presented (Figure 3). Because of air drag during the flight, the arrow kinetic energy decreases approximately 22% and the speed decreases approximately 12%. The maximum height of arrow in flight is near 2 m. The attitude angle changes from positive to negative to describe one half of a sinusoid wave. The angle of attack represents 1.1 of a sinusoid wave.

The results of modeling of bow and arrow common motion (i.e. internal ballistics) show the real range of the arrow position and speed at the instant the arrow is launched from the string. The angle of attack of the arrow ranges approximately from –0.01 to 0.01 rad, and angular speed in the vertical plane from –0.1 to 0.1 rad/s (Gros & Zanevskyy, 2002).

The developed mechanical and mathematical model of external sport archery arrow ballistics takes into account the initial angle attack and the initial angular velocity of the arrow in the vertical plane and allows investigation of their influence on the vertical coordinate of the arrow tip on the target.

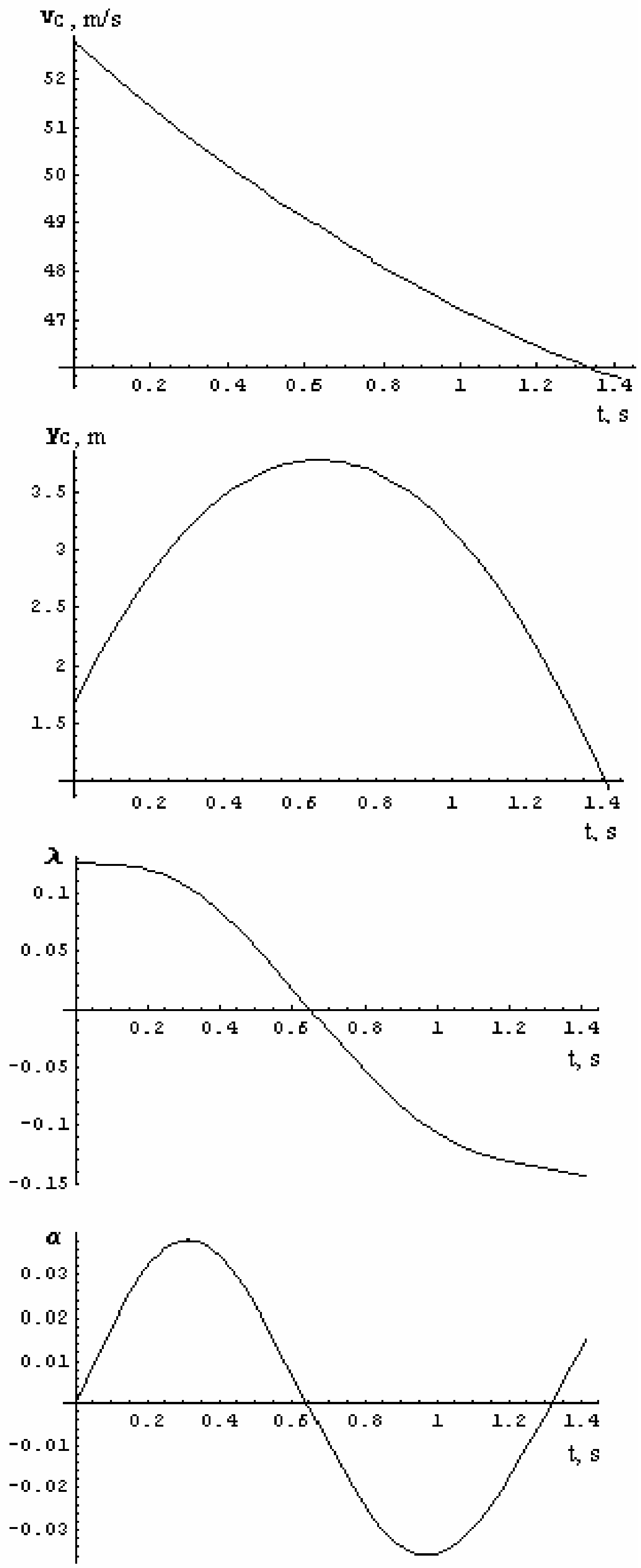

Figure 3. Plots of kinematics parameters of arrow ballistics: center of mass speed (V_C), vertical coordinate (y_C), the attitude angle (λ), and the angle of attack (α).

Consequences for practicing archery result from imitating this model of external ballistics of an arrow. The model allows study of the influence of the initial conditions on the vertical coordinate of an arrow tip on the target. The most important (Olympic) distance is 70 m. The real range of the vertical variance of arrows on the target that is caused by variance of the initial angle of attack (approximately 951–947=4 mm) is significantly smaller than the corresponding value (1004–898=106 mm) that is caused by variance of the initial angular velocity of the arrow (see Table 1).

The diameter of the main (big) target according the FITA Standard is 122 cm. The width of its rings (from 1 up to 10 points) is 122/20=6.1 cm. So, the variance of the initial angle of attack on the vertical coordinate of the arrow tip on the target will cause a range in score of approximately 4/61=0.07 points, whereas the variance of the initial angular velocity will cause a range in score of approximately 106/61=1.74 points - a difference of almost 25 times.

Table 1. Parameters of imitation modeling of arrow ballistics

$\alpha(0)$	$\lambda'(0)$	x_{CT} , m	t_T , s	y_{PT} , mm
0	0	69.713	1.41550	947
0,01	0	69.714	1.41554	951
–0,01	0	69.713	1.41548	948
0	0,1	69.723	1.41609	1004
0	–0,1	69,703	1.41504	898

The model and corresponding Mathematica computer program makes it possible to test different combinations of arrow parameters on arrow design. The type of an arrow head determines the value of the air drag force corresponding to the front drag, the arrow length and diameter determine the shear friction on the cylindrical surface of the shaft, the type fletching detemines the force of grag (see Figure A). Parameter ε shows the relationship between the mass and dimensions of the arrow shaft, head, fletching, and nock. All the mentioned parameters are accounted for in the model and play as initial parameters in the computer program that is ready for the simulation of flight of arrows of different design.

Conclusions

The developed mechanical and mathematical model of external sport archery arrow ballistics takes into account the initial angle of attack and the initial angular velocity of the arrow in the vertical plane and investigates their influence on the vertical coordinate of the arrow tip on the target.

As a result of a computer simulation based on the model, we estimated that variations in the vertical coordinate of the arrow tip on the target caused by the initial angle of attack would be about 0.07 points and caused by initial angular velocity would be about 1.74 points.

Application of the Mathematica 5 packet makes possible for couches and sportsmen, who are not familiar in methods of theoretical mechanics and mathematical analysis, to get useful results for bow and arrow tuning in the vertical plane.

Acknowledgements

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Appendix 1

Archery arrow design

A normal arrow consists of shaft with an arrowhead attached the front end, with fletching and a nock at the other (Figure A). Most modern arrows are two-and-a-half to three feet long.

The shaft is the primary structural element of the arrow, to which the other components are attached. Modern shafts are made from aluminum or carbon fiber reinforced plastic (http://en.wikipedia.org/wiki/Arrow).

The arrowhead is the primary functional part of the arrow and plays the largest role in determining its purpose. Some arrows may simply use a sharpened tip of the solid shaft, but it is far more common for separate arrowheads to be made, usually from metal, horn, or some other hard material. The arrowhead center of gravity is located far forward of the center of the shaft. This relates to two different aspects of shooting arrows, how the arrow behaves on the bow when being shot and how the shot arrow flies through the air (Tapley, 2001).

Fletching may be straight or arranged with a slight offset around the shaft of the arrow to provide a slight rotation which improves accuracy. Most arrows will have three fins, but some fletching hasfour or even more. Fletching generally range from two to six inches in length. Fletching is found at the back of the arrow and provides a small amount of drag used to stabilize the flight of the arrow. It is designed to keep the arrow pointed in the direction of travel by strongly damping any tendency to pitch or yaw.

The nock serves to keep the arrow in place on the string as the bow is being drawn. Nocks may be simple slots cut in the back of the arrow or separate pieces made from wood, plastic, or horn that are then attached to the end of the arrow.

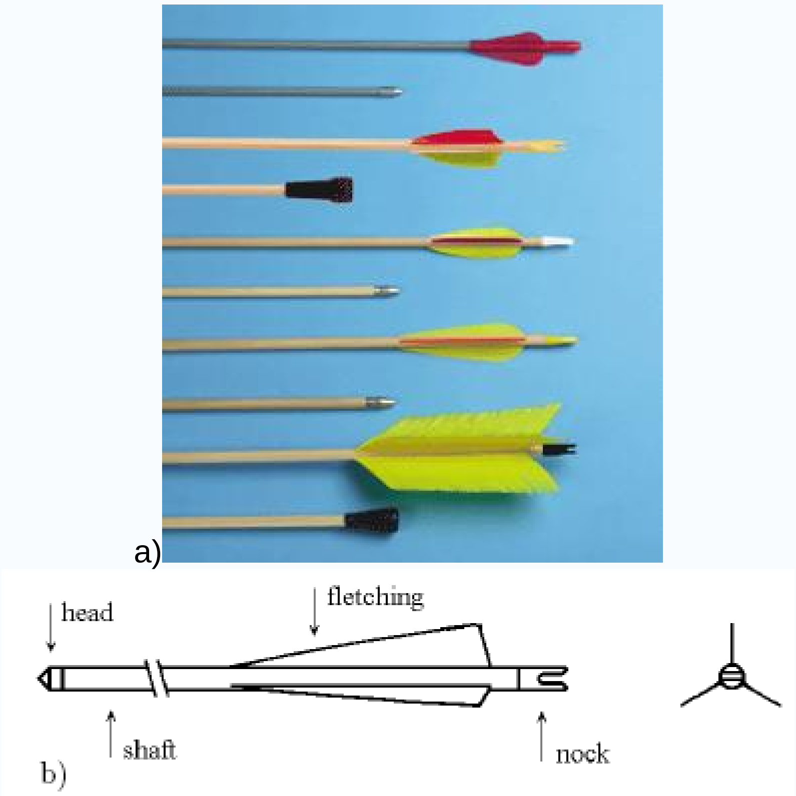
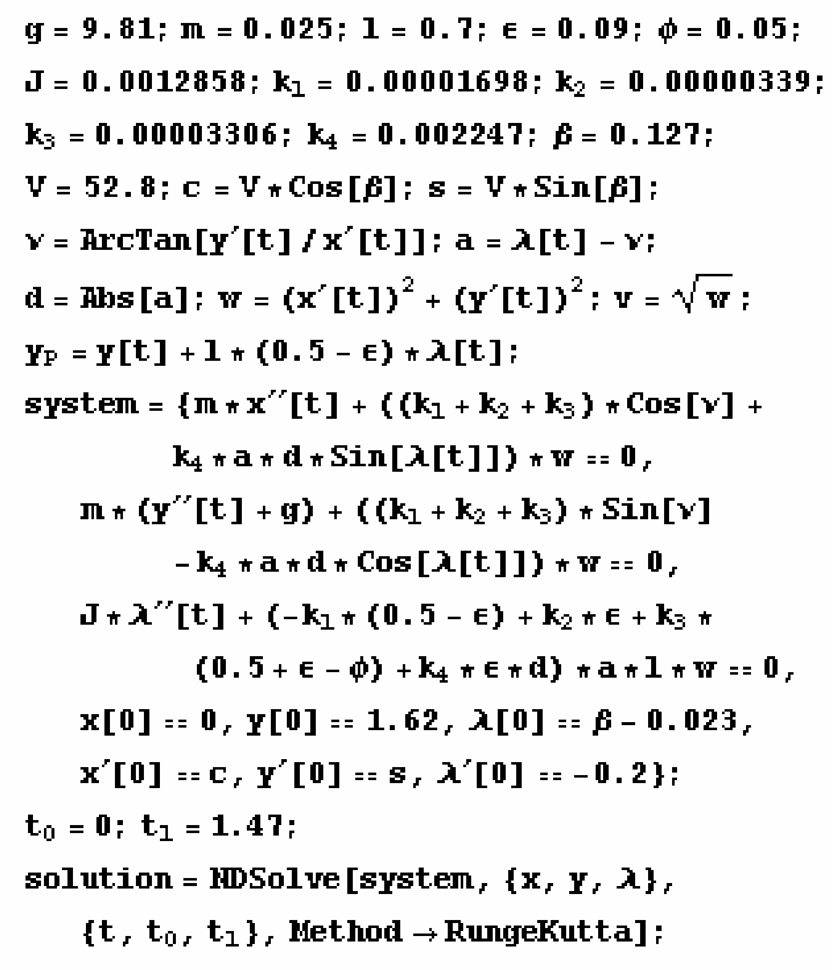


Figure A. Archery arrow: a) modern design (http://www.flaghouse.com/itemdy00.asp?T1=12874); b) common scheme (Kooi, 1998).

Appendix 2

Text of the software program Mathematica 5 on sport archery arrow ballistics



```
g = 9.81; m = 0.025; l = 0.7; ϵ = 0.09; ϕ = 0.05;
J = 0.0012858; k1 = 0.00001698; k2 = 0.00000339;
k3 = 0.00003306; k4 = 0.002247; β = 0.127;
V = 52.8; c = V * Cos[β]; s = V * Sin[β];
ν = ArcTan[y'[t] / x'[t]]; a = λ[t] - ν;
d = Abs[a]; w = (x'[t])^2 + (y'[t])^2; v = √w ;
yP = y[t] + l * (0.5 - ϵ) * λ[t];
system = {m * x''[t] + ((k1 + k2 + k3) * Cos[ν] +
            k4 * a * d * Sin[λ[t]]) * w == 0,
    m * (y''[t] + g) + ((k1 + k2 + k3) * Sin[ν]
            - k4 * a * d * Cos[λ[t]]) * w == 0,
    J * λ''[t] + (-k1 * (0.5 - ϵ) + k2 * ϵ + k3 *
              (0.5 + ϵ - ϕ) + k4 * ϵ * d) * a * l * w == 0,
    x[0] == 0, y[0] == 1.62, λ[0] == β - 0.023,
    x'[0] == c, y'[0] == s, λ'[0] == -0.2};
t0 = 0; t1 = 1.47;
solution = NDSolve[system, {x, y, λ},
    {t, t0, t1}, Method → RungeKutta];
```

Book Review – Figuring Sport

by Graeme Cohen and Neville de Mestre

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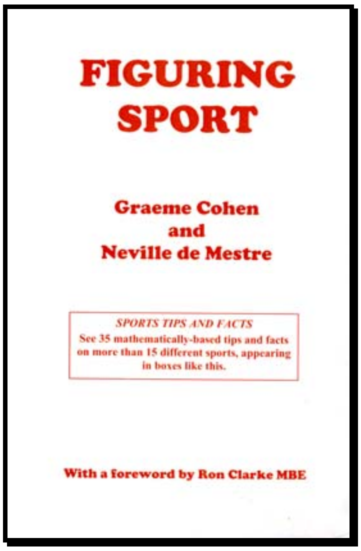

FIGURING SPORT

Graeme Cohen
and
Neville de Mestre

SPORTS TIPS AND FACTS
See 35 mathematically-based tips and facts on more than 15 different sports, appearing in boxes like this.

With a foreword by Ron Clarke MBE

Figuring Sport

Graeme Cohen and Neville de Mestre

University of Technology, Sydney, New South Wales and Bond University, Queensland

ISBN 978-0-7331-0023-9

The book covers more than 15 different sports including tennis, weightlifting, golf, darts, cricket, track and field athletics, billiards, bowls, football and rowing. As the authors state in the preface, the book is '…an attempt to show how mathematics may be used to describe, understand or predict all manner of sporting achievements and sporting organisation'. Most topics need no more than an undergraduate's or basic understanding in mathematics and physics. In addition to 35 mathematically-based tips on 15 sports, there are also suggestions for investigative projects for graduates and undergraduates of applied mathematics.

Through seven chapters, the authors consider the following topics:

In chapter 1 the probabilities of winning matches and sets are calculated, assuming that the probability of winning a single point is known. In particular, tie-breaker sets are compared to classical advantage sets and the question, which one may more likely be won, is addressed. The methods described are also applied to tennis and squash.

Four miscellaneous topics are discussed in chapter 2: weightlifting, golf, speed records and darts. First, it is investigated, how and if performance in several classes of events may be compared. Then, relative winning chances of an erratic golfer and a consistent player are determined in a match play tournament. World land and water speed records for vehicles are discussed next. Finally, the question of how to best arrange the numbers on a dartboard to give the maximum penalty for a poor shot is answered.

Two aspects of the game cricket are discussed in chapter 3. The first aspect deals with projectile theory to determine the angle and speed required to hit a ball in the air to the boundary – scoring a six. In the second part the authors provide an insight into how individual bowlers´ strike rates may be used in order to rate a team’s bowling attack.

Chapter 4 deals with athletics. Three different topics are discussed. First, the disciplines shot-put, long jump and high jump are treated within the formalism of projectile motion. The second topic is devoted to the question, where different runners should start in events on an oval track. Finally, the chapter considers triathlon. It investigates how the three events of triathlon have to be organised to be as fair as possible to the competitors’ skills.

How to strike a pool ball (snooker ball, billiard ball) such that it rolls without skidding is answered in Chapter 5. In the game of snooker special interest lies in the fact how to get out of a situation, where no direct shot is possible. The chapter explains how desnookering rectangles can be visualised at the table to get out of this particular situation.

In Chapter 6 the focus is not on practising sports but on the organisation of sports. It can be divided into 2 sections: analysis/construction of round-robin tournaments and optimising the outcome in situations given various possible constraints, e.g. choosing players for a team.

The last chapter unifies different kind of sports: bowls, cycling, football and rowing. It shows what riding a bicycle has in common with lawn bowls. In the section on football, the authors investigate, how far back to bring the ball after scoring a try to maximize the angle to the goal posts. Then, the influence of the Magnus effect on rotating soccer ball is described mathematically. Finally, a method for rigging a rowing eight (or a four) that eliminates wobble is proposed and a model of the rowing stroke is presented.

The text can be recommended for a course on mathematics in sport. It is only marginally related to computer science. However, manifold inspiring examples for mathematical, physical and biomechanical modelling in sport can be found.