Toegepaste en
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CITIUS ALTIUS SANIUS*

Injury-free exercise for everyone

**Citius Altius Sanius* (Faster, Higher, Healthier) is a variation to the Olympic motto *Citius Altius Fortius* (Faster, Higher, Stronger)

Contents

1. Overview

1.1 Title

CITIUS ALTIUS SANIUS: Injury-free exercise for everyone

1.2 Program leader

Prof.dr. F.C.T. van der Helm (TU Delft, Dept. BioMechanical Engineering; Director TU Delft Sports Engineering Institute)

Co-PIs:

Prof.dr. P.J. Beek (VU Amsterdam, Dept. of Human Movement Sciences),

Dr. D.J.J. Bregman (TU Delft; Business Director TU Delft Sports Engineering Institute)

Representatives from user groups:

Drs. K. Maase (NOC*NSF), Dr. F. Steenbrink (Motekforce Link), Dr. ir. L. Noldus (Noldus IT)

1.3 Participating organisations

Applying research institutes: Delft University of Technology (Dept. BioMechanical Engineering; Sports Engineering Institute; Motor Behavior Group; Interactive Intelligence Group; Multi-Actor Systems Group; Computer Vision Lab; Bicycle Dynamics Group; Emerging Materials Group; SMART Materials Group; Novel Aerospace Materials Group; Mathematical Statistics Group) Eindhoven University of Technology (Dept. of Industrial Design; Business Process Design Group) University of Groningen (Human Movement Sciences) Leiden University (Sport Data Centre) VU Universiteit Amsterdam (Motor Learning & Performance Group; Neuromechanics Group; Rehabilitation Research Group; Coordination Dynamics Group; Physiology Group), VU Medical Center (EMGO), AMC (IOC Center for Sports Medicine), Radboud University Medical Centre (Physiology Group)

Affiliated Universities of Applied sciences: Hogeschool van Amsterdam, Haagse Hogeschool, Fontys Hogescholen, Hanzehogeschool Groningen, Hogeschool Arnhem-Nijmegen, NHTV Breda.

Potential users, companies: Achmea, Adidas, Bosch, Cinoptics, Dopple, Plux, Fit!Vak, Royal Dutch Gazelle, Inmotio Object Tracking, IZI BodyCooling, Motekforce link, ManualFysion, MyLaps, MyTemp, NedCard, Noldus, Qualogy, VirtuaGym, 2M Engineering, NovioSens, Borre.

Potential users, sports organizations: NOC*NSF, International Tennis Federation, Royal Dutch Baseball Association, Royal Dutch Hockey Association, Royal Dutch Football Association, Royal Dutch Lawn Tennis Association, Royal Dutch Watersports Federation, Golazo Sports SX, Zevenheuvelenloop Foundation, Nijmeegse Vierdaagse Foundation, Team Sunweb.

Potential users, knowledge institutes: InnosportLab Sport en Beweeg, Sailing Innovation Center, Reade Rehabilitation, SWOV, Kenniscentrum Sport.

Potential users, other: Gemeente Amsterdam, Gemeente Eindhoven,

1.4 Program costs

Requested budget NWO-domein TTW € 4 000 000	Cash contribution - € 786 324	In kind contribution - € 1 777 727
Program duration – 5 year	Number of projects - 9	

Position	TUD	VU	RUG	TU/e	RAD	LEI	Total
Number of PhDs	8	4	1	1	1		15
Number of postdocs	2					1	3

1.5 Keyword(s)

Wearable sensors, data science, augmented feedback, sports participation, physical performance, health, injury prevention

2. Summary

2.1 Summary

The prevailing lifestyle in the Western world (immobility, unhealthy eating, smoking and drinking habits) is an important factor in the etiology of many chronic diseases. Physical activity through sport participation helps to reduce this risk, but introduces new risk factors associated with exercise related injuries. The aim of the program "Citius, Altius, Sanius" is to stimulate people of all performance levels to engage in and sustain physical activity through sports and fitness, improve their performance and prevent injuries by providing informative and motivating information using advanced sensor and data science techniques. The information provided is tailored to the individual user, taking into account his or her characteristics, using effective feedback methods. Innovative unobtrusive wearable sensors (in clothing, and advanced cameras) will be used to estimate the load. Data science techniques will relate the load to injury mechanisms, and provide an individual training advice to stimulate the sporter and prevent injuries, or return to sport quicker. Six applied projects are defined incorporating the activities with most injuries. Sports associations, sports medicine and physical therapy, but also many small-to-medium-sized companies are involved to commercialize this innovative approach for top and recreational athletes, but also for rehabilitation patients.

2.2 Unique selling point(s)

- **Scientific excellence**: strong researchers advancing the state-of-the-art.
- **Team effort**: fundamental and applied projects intertwined.
- **Fundamentally interdisciplinary**: engineering (sensor technology, data-science, feedback-systems), behavioral and movement sciences (physiology, biomechanics), sports medicine.
- **Strong user participation**: 21 companies, 12 sports associations and 2 city councils.
- **Focused program**: targeting key sports and high-incidence injuries.
- **Broad impact**: amateurs, professionals, paralympics.

3. Program description

3.1 Scientific challenges

Physical activity is the best medicine to prevent health problems across the lifespan: it is more efficient than cure or rehabilitation, both from a health and an economic perspective. The goal of the present program is to stimulate people to start and continue participating in sports by providing motivational and informational cues about their performance, using (big) data science and unobtrusive sensor technology. Simultaneously, personalized information, based on a combination of individual and cohort data, will be provided to recreational and elite athletes to reduce the risk of injury and overload.

There is a clear trend towards individualized sports participation. Tailoring information to individual needs regarding physical activity is therefore crucial. Modern sensor technology and data science, as well as web solutions and apps like Strava, provide opportunities for obtaining this tailored information. The internet enables comparison with peers of the same age, gender, experience, objectives, etc., as well as the full history of previous performances in the cloud. Knowledge about performance improvement is a highly stimulating factor that contributes to lasting engagement and attaining higher performance levels.

The challenges in promoting healthy participation in physical exercise are twofold: (1), to provide engaging information about the athlete's physical and performance improvement, and (2) to ensure that no injuries will occur. Although injuries prevail in many sports (see Section 4.1), little is known about their relationship with physical load.

Hence, there is a clear need to strengthen the information chain from sensor information, via data science and analysis to informative feedback applications, which we will pursue in three fundamentally oriented projects. This not only requires innovative research on each of these components, but also on the effectiveness of the resulting information chains. For the latter purpose, we will perform research in six sports-related domains with a high prevalence of injuries. The general relationship between physical exercise and injury incidence in these domains will be investigated by acquiring large amounts of data using new sensor technology, and will then be tuned to individual athletes using

their individual data. The resulting individualized information will be fed back to the athlete in order to improve performance in a healthy manner. The feedback in question will be based on novel technological possibilities, including virtual and augmented realities, as well as novel psychological insights regarding mechanisms of behavioral changes.
WIthin each of the fundamental projects, innovative devices or mathematical approaches will be developed. Within the applied project, these innovations will be combined, and applied to six different sport specific domains to motivate athletes and to prevent injuries. This general approach in the applied projects is very novel, especially on the large scale as applied in this program.

3.2 Research lines

General approach

The program is built around three fundamental projects (P1 - P3) on sensing, data science and feedback (see Fig. 1). Six applied projects (P4 - P9) have each a similar approach, combining the knowledge of these three fundamental projects. The applied projects are each in different sport-related domains, covering most occuring sports injuries in The Netherlands.

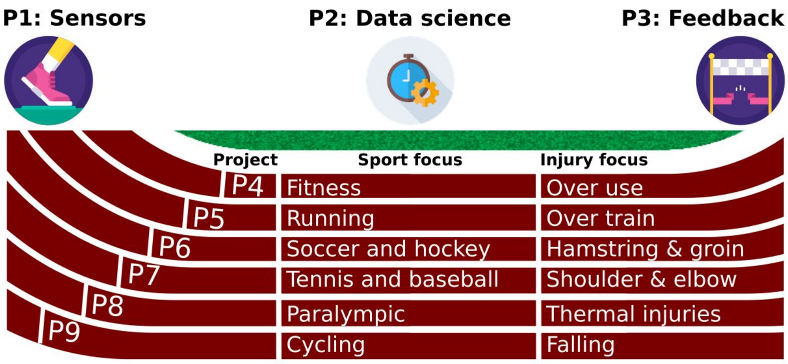


Figure 1: The Citius, Altius, Sanius program combines three fundamental research lines (P1: Sensors, P2: Data science, P3: Feedback) with six applied research lines (P4-P9) focussing on specific sports and injuries.

Fundamental projects

Sensing (P1): The magnitude, duration and frequency of the physiological load is recorded using cheap and unobtrusive sensors. A major challenge is that the sensors can be used in daily sports activities or even during matches, without interfering with these activities, and that they are cheap enough to be widely used. The physical status of the athletes will be obtained using questionnaires by app, in which the athletes provide information about physical constraints, location, type of disorder, but also other factors like stress, sleep and fatigue. Also we will investigate if information about the physical status can be retrieved from facial expressions, skin color and physiological recordings like heart rate and sweat (in collaboration with P4 (fitness and strength training).
Data science (P2): A major role in the program will be for data science, combining the wealth of data about physiological load and physical status.
Firstly, the physiological load and physical status will be used to develop models for predicting injury mechanisms, e.g. what type of (sustained) loading is likely to result in injuries. Sports physicians and physical therapists will help to direct the search for injury mechanisms.
Secondly, predictive models will be developed, to apply the knowledge about injury mechanisms for individual athletes. Here, general factors like gender and age are likely to be important, but also athlete specific factors like physical condition, amount of training, physical strength, etc. The predictive models will be used for individual athletes to calculate the injury risk as a probability. If the risk probability starts to increase, the training schedule should be adapted.
Feedback (P3) is crucial to inform and motivate athletes, so as to achieve behavioural change in the short and long run. Feedback will be about the performance, e.g. using avatars (virtual reality), visualized information to improve movement execution (augmented reality) or auditory or tactile cues, to show previous performance, or relative performance with regard to the peer group. Feedback will also be provided to control the risk of injury. If the injury probability is increasing rapidly, a new individualized training protocol will be advised, or even quitting the training or match.

Sport-specific approach: We selected six sport-specific domains which cover most injuries (high risk and/or many athletes) in The Netherlands. The knowledge obtained in each of the six sports-specific domains will be generalizable to other domains (cross-fertilization). Each of the projects has

innovative aspects. Cross-fertilization between the innovations per project will be sought.
P4: fitness and strength training. Musculoskeletal models will be used to calculate the internal load in the human body from the external load (motions, forces) as being recorded. Facial expressions and skin color will be used to assess the physical status of the athlete, instead of questionnaires.
P5: running. Recreational runners will be monitored 24/7, not only to assess the results of running exercises, but also to relate this to healthy lifestyle parameters.
P6: team sports (soccer, field hockey): Focus will be on one frequently occurring injury related to physical overload, i.e. hamstrings injuries. A special garment with wearable sensors will be developed, recording very specifically the movements (accelerations, muscle activity) of the athletes. The garment can be easily used during practice and matches, and should be washable.
P7: coordinative sports (tennis, baseball): Focus will be on upper extremity injuries to the elbow and shoulder. A wearable sleeve and force transducer in the racket will provide information about load and motion, and feedback will be given to improve motion execution to prevent (recurrence of) upper extremity injuries.
P8: heat stroke. Skin temperature is most indicative predictor of heat stroke. It can be recorded using wearable sensors in garments, or using camera systems in a large running event. A cooling vest will be developed, which directly regulates body temperature based on sensor information. Application will be for endurance athletes in extreme weather conditions, but also for spinal cord injured subjects, who have very often temperature regulating problems due to impeded sensory function and blood flow.
P9: falling during cycling. In some sports most injuries do not occur through sustained loading, but are event-related, and are therefore difficult to predict. Nevertheless, they can be prevented by specific training or devices. P9 is focussed on cycling. An augmented steering device will be developed to stabilize the bicycle at very low speeds, easing elderly to mount and dismount. Special descend training for professional cyclists will allow them to perform better at a greater safety level.

Individualized athlete approach: The capacity of humans to perform perceptual-motor tasks and activities varies greatly across individuals as a result of differences in physical and mental characteristics, exercise history, and age. There exists a human performance continuum, ranging from physically challenged and deprived individuals to elite athletes. One's position on this continuum is not fixed but might be improved via exercise and training. However, striving to improve one's performance brings along a risk of injury, which has different characteristics depending on one's initial performance level, personal risk factors and objectives. For example, sedentary individuals who decide to engage in physical activity may be confronted with injuries due to overloading because their body is not used to exercise, or because they employ incorrect movement techniques. Likewise, in recreational and elite athletes the risk of injury may be enhanced when they start training more vigorously to increase their performance level, while in elite athletes the readiness to take risks is generally higher, thus increasing the chance of injury. At all these levels, adequate feedback about one's physical and mental performance status, combined with adequate feedback about training intensity and performance technique, may curtail the risk of injury, with benefits to both individual and society.
When athletes return from an injury, the load capacity might be severely reduced. For these athletes the training load needs to be very precisely determined related to the severity of the injury. At first, expert input from sports physicians and physical therapists is needed. In P2 (data science) also these relationships can be learned from the expert input.

3.3 Description and coherence of the projects

Like in sports, successful science is a team effort. The challenge of realizing true injury prevention and increased sports participation can only be addressed by a multidisciplinary team of excellent scientists dedicated to combine their expertise in engineering, data science, psychology, sports medicine, biomechanics and human movement control. Figure 2 shows the coherent interaction between fundamental and applied projects with different scientific background needed to tackle this challenge. We need psychologists to help us understand human learning in the context of adapting motion behavior and cooperation to participate in the program and share their data. We need engineers to design innovative sensors and feedback mechanisms, data scientist to process and visualize the wide amount of data collected. We need sports physicians and physical therapists to provide insight in injury mechanisms, and human movement scientists to have insight in biomechanics, physiology and musculoskeletal modelling. These scientists need to work closely together across domain boundaries, to guarantee the essential teamwork needed for integrating all the data and knowledge in the program.

The overarching objective of the three fundamental research projects (P1-P3) is to develop innovative technologies and feedback solutions. The objective of the six applied projects (P4-P9) is to integrate the fundamental technology in six different sports domains, focusing on performance, participation, improvement, and injury prevention. The fundamental projects and the applied projects will run in parallel and profit from each other without the overall success being critically dependent on the progress made in any individual project. Fundamental research projects focus on novel unobtrusive sensor technology (P1), (big) data science (P2) and feedback technology (P3). Six application domains have been defined, covering injury-prone physical activities: fitness & strength training (P4); endurance sports (P5); team sports (P6); coordination sports (P7); temperature control (P8); and fall prevention & protection (P9).

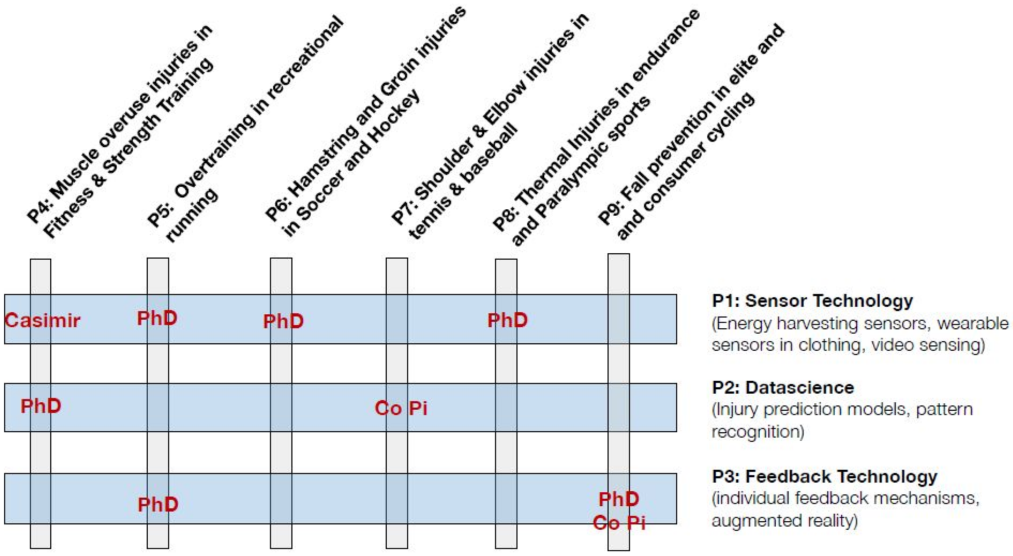


Figure 2: Three fundamental research projects (Sensor Technology, Data Science & Feedback Technology) will be integrated in 6 applied research projects, by exchanging information in joint meetings and by co-supervising PhDs and postdoctoral fellows (see also Table 6.1).

3.4 Risk management and contingency plan

Measures have been undertaken to minimise potential risks that could affect the program:

1) Citius Altius Sanius acts along two main research lines: fundamental and applied. Sensing, data science and feedback are strong fundamental lines, supplying the applied projects with knowledge. If the foreseen implementation for an applied project does not work out, alternatives will be searched in collaboration with the fundamental research lines. Strong cross-fertilisation is needed between projects within both research lines, but projects are designed in such a way that delays in one project do not limit progress in the others.

2) To promote cross-fertilisation, part of the scientific personnel is shared between projects. Yet, responsibility for each appointed person is clearly defined at the level of the individual projects and project leaders, often sharing the supervision of a PhD student or PostDoc.

3) The Program Council, consisting of all project leaders and the program leader, and meeting at least four times per year, will monitor progress, enable cross fertilization and undertake appropriate joint action in case of setbacks.

4) Business representatives will be part of the Project Teams to ensure the utilization of the scientific results and designs, and act as advisors for business-related financial issues and IP issues. Furthermore, a yearly two-day symposium will be organized for all CAS participants (scientists, engineers, clinicians and business representatives) to facilitate cross-fertilization between projects and between the different stakeholders like sports associations, companies and health-care institutions.

3.5 Uniqueness of the proposed program

The proposed program will be the first nationwide sports-related research program promoting sports participation and preventing injuries. A unique selling point of the program is the intense interdisciplinary collaboration between hardware and software engineers on the one hand and behavioral scientists on the other. Current research and applications are less effective due to the absence of such cooperation. The program holds the promise of setting a new standard to data-intensive, personalized feedback solutions in the domains of sports, exercise and health with substantial societal and economic value.

Table 1 Schematic overview of the program

Projects	Research groups	Potential Users
	Fundamental research lines	
P1. Sensor technology for unobtrusive athlete monitoring	a. Delft University of Technology - Materials engineering: Prof. W.A. Groen, Dr. S.J. Garcia - Devices, electronics: Prof. P.J. French, Dr. A. Bossche - Computer vision: Dr. J.C. van Gemert	Adidas, Motek Force Link, Nedcard, Noviosense, Borre, MyLaps
P2. Data science for injury prevention and performance improvement	a. Leiden University - Computer science: Prof. J.N. Kok. Dr. A.J. Knobbe b. Delft University of Technology - Statistics: Prof. G. Jongbloed; Dr. F.H. van der Meulen	MyLaps, KNLTB Qualogy
P3. Personalized feedback that works	a. Vrije Universiteit Amsterdam - Human movement sciences: Prof. P.J. Beek b. Delft University of Technology - Interactive intelligence: Prof. C.M. Jonker - System engineering: Dr. S.G. Lukosch	Cinoptics Noldus Dopple Twnkls
	Focused use-case inspired research lines	
P4. Show your muscles! Fitness & strength training	a. Delft University of Technology - Biomechanical engineering: Prof. F.C.T. van der Helm b. Vrije Universiteit Amsterdam - Human movement sciences: Prof. H.E.J. Veeger	Motek Force Link, Watersportverbond, Sailing Innov. Center, VirtuaGym, Fit!Vak, Plux, Noldus
P5. Run - Work - Sleep - Repeat: 24/7 monitoring for healthy running	a. Eindhoven University of Technology - Industrial design: Prof. S.B. Vos; Prof. A. Brombacher b. VU University Medical Centre - Public and Occupational Health: Dr. E.A.L.M. Verhagen	2M Engineering Golazo Sports SX InnoSportlab Sport & Beweeg, Gemeente Eindhoven
P6. Reducing hamstring injuries in soccer and field hockey using smart sensor shorts	a. University of Groningen - Human movement sciences: Prof. K.A.P.M. Lemmink b. Delft University of Technology - Materials engineering: Prof. K.M.B. Jansen c. Vrije Universiteit Amsterdam - Movement sciences: Prof. G.J.P. Savelsbergh d. KNVB - Sports medicine: Dr. E. Goedhart	KNVB KNHB Inmotio
P7. Breaking the high load - bad coordination multiplier in overhead sports injuries	a. Vrije Universiteit Amsterdam - Human movement sciences: Prof. H.E.J. Veeger b. Delft University of Technology - Biomech. engin.: Prof. F.C.T. v/d Helm, Dr. D. Bregman c. VU University Medical Centre - Public and Occupational Health: Dr. E.A.L.M. Verhagen	Motek Force Link Plux KNLTB KNBSB ManualFysion ITF
P8. Monitor and prevent thermal injuries in endurance and Paralympic sports	a. Vrije Universiteit Amsterdam - Human movement sciences: Prof. H.A.M. Daanen; Prof. T.W.J. Janssen; Dr. M.J. Hofmijster b. Delft University of Technology - Materials engineering: Prof. K.M.B. Jansen c. Radboud University Medical Centre - Physiology: Prof. M.T.E. Hopman, Dr. T.M.H. Eijsvogels c. NOS*NSF Dr. M. Moen	NOC*NSF Team Sunweb Watersportverbond Sailing Innovation Center St. Zevenheuvelenloop Nijmeegse Vierdaagse Reade Rehabilitation MyTemp IZI Body Cooling
P9. Fall prevention in elite and consumer cycling	a. Delft University of Technology - Bicycle dynamics: Dr. A. L. Schwab - System engineering: Dr. S.G. Lukosch - Sports engineering: Dr. D. Bregman	Royal Gazelle Bosch Team Giant Sunweb SWOV

	b. University Medical Center Groningen - Clinical Neuropsychology: Dr. R.B. Huitema c. NHTV Breda University of Applied Sciences - Mobility Research: W.J. de Kruijf	

The program is also unique because it addresses the objectives of lasting engagement, performance improvement and injury prevention in an integral manner, with a focus on the properties, capabilities and needs of the individual user. This integral approach requires that a wide range of scientific disciplines, ranging from technical to behavioral sciences, are combined to achieve these objectives in the best possible way. Input from end-users is assured via the strong participation of many sports associations and the overarching National Olympic Committee (NOC*NSF), engineering and software companies, healthcare institutions and insurance companies.
The program will relate large amounts of data from all participants to individual predictions and adapted training protocols.Therefore the sporters can benefit from the large scale of data acquisition, which will motivate athletes to enter their own data as well.

4. Program consortium

4.1 Scientific community

The scientific consortium behind the present program is strongly multidisciplinary in nature and houses all the expertise required for realizing its objectives. TU Delft brings state-of-the-art expertise in sensor technology (P1), data science and analysis (P2) and virtual and augmented reality environments (P3), along with dedicated expertise in sports biomechanics and engineering (P4, P7, P9) to the program. VU Amsterdam and RU Groningen both have a long tradition in multi- and transdisciplinary research on sports and exercise, involving biomechanics, exercise physiology, psychology and sports medicine. Both have a focus on injury prevention, team sports (P6), explosive sports (P7) and adapted physical activity (P8). In addition, VU brings in specific expertise in perceptual-motor learning (P3, P4, P5, P6, P9), muscle physiology, muscle-joint biomechanics (P4, P7), and thermoregulation (P8). Leiden University (LEI) is a front runner in data and model management, data mining, bioinformatics and computing (P2), and shares a newly established Sport Data Center with TUD and VU. RUG, VU, TUD and LEI have all recently been recognized by ZonMw as national sports innovation centers with strong collaborations with applied universities having a training in physical education (among which universities of Applied Sciences HHS, HvA, HH, Fontys and HAN). TU Eindhoven and UMC Radboud bring in specific expertise with regards to recreational running (P5) and thermoregulation (P8), respectively. Contributions in the Sports Medicine field will be ensured by the International Olympic research center for sports medicine at AMC and VUmc (P4, P6, P7), and from sports physicians from the UMC Groningen (P6), as well as from the sports physicians from the sport associations. All projects of the program entail new collaborations among technological engineers, human movement scientists and (para)medical specialists.

Discipline	Domain	P1	P2	P3	P4	P5	P6	P7	P8	P9
Engineering	*Materials*	X					X			
	Electronics	X	X							
	Feedback	X		X						
	Biomechanics				X			X	X	X
	Sports									X
	Industrial design					X				
Data science	*Data science*		X							
Movement science	*Human movement sci.*			X	X		X	X	X	
	Physiology								X	
Psychology	*Neuropsychology*									X
Medicine	*Occupational health*					X		X		
	Sports medicine						X			

4.2 User community

The user community of the program comprises a broad variety of stakeholders, including the national sports council NOC*NSF, sports federations like the KNVB, the KNBSB and the KNLTB, including their athletes and coaches, city councils, sports-medical associations, insurance companies, fitness companies, sports equipment companies and sensor and gaming companies. All of these stakeholders take a strong interest in the program and are keen on contributing to its success. This is reflected in their support letters and the substantial in kind and in cash contributions they agreed to make. The sports councils are interested in increasing participation in their sports and in healthy ways of increasing performance in both recreational and elite athletes, and are strongly committed to facilitate investigations and measurements in their respective domains. Cities with a strong health agenda support the program because it fits their policy to improve public health through increased participation in sports and exercise; where feasible they will provide infrastructural support to the program. Sports-medical associations are interested in improving athletic and public health and in developing relevant knowledge and applications for that purpose, and are very willing to bring their expertise to the program. The incentives of companies to participate include R&D, co-development of equipment, and generating and sharing knowledge to support, develop and improve their products. To this end, they will make their prototypes and existing products and expertise available to the program.
Three stakeholders have adopted the research program as a whole. The Netherlands Olympic Committee (NOC*NSF) has sponsored the research program on behalf of all Dutch sports participants, since they strive for more and safer sports participation. Kenniscentrum Sport also provides a large in-kind contribution (128k€) for knowledge dissemination by translating the scientific knowledge obtained in the research projects to the sport community. The insurance company Zilveren Kruis Achmea will distribute the information about injury prevention through their widely used app.
The proposed program will be one of the largest and most multidisciplinary programs worldwide. Internationally operating companies like Adidas and Bosch, as well as the International Tennis Federation (ITF) were attracted to the program.

5. Impact

5.1 Application perspective at the program level

Economic and societal impact of the program

The prevailing lifestyle in the Western world (immobility, unhealthy eating, smoking and drinking habits) is an important factor in the etiology of many chronic diseases. Physical activity through sport participation helps to reduce this risk, but introduces new risk factors associated with exercise-related injuries. In the Netherlands, the direct medical costs due to sports injuries are 460 million € per year. The indirect cost, are estimated to be 1,3 billion € per year (See: veiligheid.nl). We have assembled the major injury-prone physical activities in our program, being fitness, cycling (falling), soccer, tennis and running - covering 75% of all sport-related injuries. Based on these figures, a 10% reduction of the injuries in these domains will yield an economic benefit of around 120 million € per year (direct and indirect costs combined).
Lack of physical exercise is a well known problem among adolescents. For elderly, disuse is one of the major reasons for physical deterioration, with lack of mobility reducing the quality of life and socializing. Our research program focuses on recreational athletes, but also on elite athletes and athletes recovering from an injury. Reducing injuries aside, increasing physical activity within the general population promotes health (and thus reduces health-care costs) and improves mobility among the elderly, adding to the quality of life.
It is highly likely that our broad approach will have a significant impact on sports participation and will reduce the economic losses due to sports injuries. New means of providing information (e.g., via the internet, apps and social media) will help to disseminate our results to relevant user groups.
Moreover, we have wielded a unique ecosystem with internationally operating companies, sports associations, sports-medical associations, together with university research teams in engineering, human movement science and sports medicine. The research activities will not only lead to advances in sensor technology (e.g., energy-harvesting), data science (e.g., predictions models generating

individual-tailored advice), feedback technology (e.g., augmented and mixed realities for personalized feedback incorporating the latest insights about learning and behavioral change), but also to a better integration of the resulting information chains than have been accomplished to date. The entire information chain from sensors, via data processing to user feedback will be integrated in novel products, which will be beneficial to specific sports and exercise domains but will also lead to generic solutions. The strength of the Citius Altius Sanius program is that novel techniques will be developed and tested in applied contexts, resulting in dedicated and evidence-based applications, that will represent and generate economic value.

In all likelihood, the proposed research program is the largest program on performance improvement with injury prevention worldwide, and the most interdisciplinary to boot. For this reason, international companies like Adidas, Bosch and Plux are keen on participating along with many smaller, national companies. They see a clear need to strengthen the components of the information chain as well as their integration with respect to the individual user. In total, more than 2 M€ in in-cash and in-kind contributions were received from companies and sports association, which is a clear indication of the foreseen societal and economic impact of this program.

Utilisation perspective of the results

As described in the previous section, there is clear and strong utilisation perspective for the results of the program, both in terms of dissemination to relevant user groups and in terms of the development of products with potential market value.

With regard to the dissemination aspect, several companies (e.g., VirtuaGym, Zilveren Kruis Achmea) have launched apps to inform athletes about superior training protocols for performance improvement with reduced risk of injury. Our research program is likely to collect a wealth of new information about these aspects, which will help to improve the apps in question and other forms of communication. In addition, the focus of the program on the individual user fits in with the current trend away from organized sports to individual, self-organized sports participation. As a case in point, the largest groups of recreational athletes are currently found in fitness, running and cycling. Informing these athletes about their physical status, performance (improvement) and the risk of developing injuries will increase their knowledge about the effects of their activities and enhance their compliance to exercise.

With regard to product development, it is remarkable how well the present program has been received by a broad spectrum of companies that are active or considering to become active on the sports and exercise market. All of the partnering companies have a vision as to how they can contribute to the program as well as its potential for the development of new products and their marketing. To highlight a few concrete examples, companies like Adidas and Gazelle are keen on incorporating a new generation of sensors in shoes, clothing and equipment, aiming for mass production. IZI body cooling and MyTemp will focus on temperature sensors to be swallowed. IT companies like Motekforce Link, Noldus IT b.v., Mylaps, and Qualogy are able to integrate data processing techniques to user feedback programs, while Cynoptics, twnkl and Dopple hold high expectations with regard to the development of advanced feedback solutions that combine high-end technological aspects (e.g., augmented and mixed realities) with current knowledge about engagement, learning and lifestyle change.

Public-private collaboration

The Citius Altius Sanius projects have been defined in close collaboration with companies and end users like sports associations and sports physicians. Each project has representatives from each user group. The program users are both from larger companies such as Adidas and Bosch, but mostly about 20 small and medium sized companies such as Noldus IT b.v. and Motekforce Link as well as start-ups such as Dopple. In Citius Altius Sanius, three academic medical centres (Radboud UMC, AMC and VUMC) closely work together in the overall program with engineering universities and human movement science groups. In addition, all individual projects are executed in close collaboration between at least two knowledge institutes and most of the projects even three.

5.2 Utilisation plan

In the applied projects (P4-P9), actual user needs in a wide variety of sporting disciplines are central to the research goals, ensuring a short time to implementation for the novel technologies for the fundamental innovations (P1-P3).

The ‘Kenniscentrum Sport’ (funded by ministry of Public Health and Sports) will spread the program outcomes to the whole Dutch sporting community. The Dutch National Olympic Committee (NOC*NSF) will spread the program outcomes to the Sports Physicians, coaches and recreational and elite sporters. NOC*NSF will organize twice per year the main CAS program meeting in the Dutch national sports center in Papendal. In addition, NOC*NSF will set up platform meetings for embedded scientists in sport associations, discuss relevant findings in the National Coach Platforms and during sports medicine Master classes.

It is estimated that we will reach out to **80% of active sports participants in the Netherlands** through the participation of the branch organisation in fitness (Fit!Vak) and major sports associations in cycling (SWOV), football (KNVB), tennis (KNLTB), baseball (KNBSB), sailing (Watersportverbond) and field hockey (KNHB). Sport-medical companies like Plux and ManualFysion, rehabilitation center READE and the medical staff of the sports associations actively participate in the program, for the diagnosis and treatment of sports injuries. The international impact of the novel technologies is ensured by participation of multinational companies as Adidas, Bosch, Noldus IT, Motekforce Link and Gazelle (PON).

VirtuaGym will incorporate information about performance and individually adapted training protocols in their app. Zilveren Kruis Achmea (the largest Dutch insurance company) will share relevant findings from the research program with their clients via mailing and sports-specific newsletters. They will also incorporate the results of the program in their Injury-app.

5.3 Sense of urgency

The sense of urgency of the CItius Altius Sanius program is mainly dictated by the disease burden of our ageing society, in which the incidence of diseases increases with the ageing of society, while both adolescents and elderly are less and less engaged in sports and physical activities. Providing motivational tools and simultaneously preventing injuries might be a reversal to this trend.

Our current 24/7 economy puts constant pressure on a healthy and active lifestyle. Each individual has to combine the demands of family, with the demands of work, social life, leisure time, sleep, etcetera. Moreover, a considerable number of adults sees their lack of sports and physical activity as a personal failure. Participating in sports has also been changing in the last decades, from organized activities planned well in advance towards more individually chosen moments of participation. However, then the joint feeling of doing sports together is lacking, leading to less motivation and more often dropping out of physical activities. There is a tendency that athletes share more of their activities through internet, like Strava in cycling, and receive feedback information about their performance with respect to their peer group. In the current program, the feedback information is taken to the next level, which much more detailed information about performance and how to improve, whereas also tailormade advice is given how to prevent injuries.

The sense of urgency for this program, however, is also dictated by the readiness of technology to allow a next step in the development of wearable sensors, data science and feedback. Research in the Netherlands in the field of sports engineering is at an internationally leading level, with leading groups in sports medicine, human movement science and sports engineering.

In the Netherlands, but also worldwide, major breakthroughs are taking place in the field of sports. We have assembled a large consortium of relevant scientists, unequalled in the world. Large international companies like Adidas and Bosch have recognized the exciting potential in the Netherlands. This also provides opportunities to Dutch companies to maintain or increase their market share internationally.

Participating companies such as Motekforce Link are worldwide market leaders in the field of advanced rehabilitation technology, and want to widen their activities to a broader range of physical activities. The network within the consortium will not only bring researchers and end-users together, but all companies so that, innovations from different companies can effectively be combined into new products, increasing the economic position and strength of the Dutch sports equipment industry. This is especially important since in the Netherlands there are relatively many but generally small to medium-sized companies.

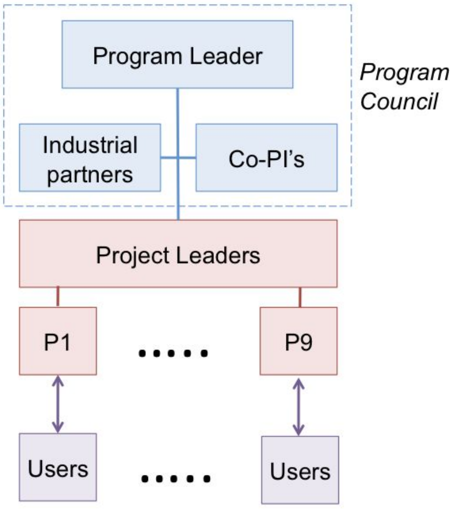
6. Programmatic approach

6.1 Added programmatic value

The Citius Altius Sanius program encompasses six multidisciplinary projects addressing the three fundamental research projects of sensing, data science and feedback monitoring. Each project has its own project leader and user committee, which will meet twice a year. The program as a whole brings together a unique span of scientific and sports disciplines, providing added value over projects that focus on single sports-related domains or zoom in on a single innovation. To enhance coherence and guarantee optimal knowledge sharing between fundamental and applied projects, part of the scientific personnel is shared between institutes. Within the research lines (sensing, data science, feedback) there will be quarterly meetings with all PhD, Postdocs and project staff from the applied projects, in order to bring them up-to-date with new developments in the field, to exchange information between the projects, and to decide on new joint research approaches.

6.2 Management structure

The nine project leaders together with the Program Leader (Prof.dr. F.C.T. van der Helm) and co-PIs (Prof.dr. P.J. Beek, Dr. D. Bregman) will form the Program Council, meeting at least four times a year for strategic decisions and to enhance interaction between projects. This Council will also include representatives of the industrial partners.



6.3 Programmatic activities

Researchers of all projects will meet once a year to exchange information during a Program Symposium. Each year a Summer School will be organized for the PhD students and postdocs with internationally renowned scientists. Near the end of the program, workshops and/or session will be organized at conferences sport-related (ECSS, ISEA) or relevant medical disciplines e.g. sports medicine.

7. Financial planning

Budget	**Requested from NWO-domain TTW**	**Co-funding** (for details, see project descriptions)
Program activities	**Total budget: € 60.000** 4 x symposium: € 25.000 4 x summer school: € 25.000 Final workshop: € 10.000	**In kind:** - Achmea: € 87.200* - Kenniscentrum Sport: € 128 000* (* not included in project budgets)
Project 1	**Personnel positions:** *- 1 PhD(1.0fte): € 191.364* *- 1 PhD(0.8fte): € 153.091* *- 1 PhD(0.5fte): € 95.682* *- 1 NWP(0.5fte):€ 47.076* **Consumables:** *€ 147.500* **Travel abroad:** *€ 24.000* **Investment:** *€ 0*	**In cash:** - Adidas: € 75.000 - Mylaps: € 20.000 - Nedcard: € 15.000 **In kind:** - Adidas: € 75.160 - Mylaps: € 40.280 - Motekforce Link: € 43.600 - Nedcard: € 20.000 - ByBorre: € 41.400 - NovioSens: € 75.000

Project 2	**Personnel positions:** *- 1 PhD(1.0fte): € 191.364* *- 1 PhD(0.5fte): € 95.682* *- 1 PD(1.0fte): € 126.432* *- 1 NWP(0.5fte):€ 114.792* **Consumables:** *€ 0* **Travel abroad:** *€ 26.000* **Investment:** *€ 0*	**In cash:** - Qualogy: € 80.000 - Mylaps: € 20.000 **In kind:** - Mylaps: € 40.280 - KLNTB: € 21.800
Project 3	**Personnel positions:** *- 1 PDEng(1.0fte): € 87.540* *- 1 PhD(0.5fte): € 95.682* *- 1 PhD(1.0fte): € 191.364* **Consumables:** *€ 41.000* **Travel abroad:** *€ 25.000* **Investment:** *€ 0*	**In cash:** - Noldus: € 42.500 - Dopple: € 24.000 **In kind:** - Noldus: € 131.862 - Cinoptics: € 20.928 - Dopple: € 56.500 - Twnkls: € 20.710
Project 4	**Personnel positions:** *- 1 PDEng(1.0fte): € 87.540* *- 1 PhD(1.0fte): € 191.364* *- 1 PhD(0.5fte): € 95.682* **Consumables:** *€ 193.073 including Casimir PhD* **Travel abroad:** *€ 26.000* **Investment:** *€ 0*	**In cash:** - Motekforce Links: € 70.000 - Noldus: € 12.824 **In kind:** - Motekforce Link: € 21.800 - Watersportverbond: € 20.100 - Sailing Innovation Centre: € 19.000 - Noldus: € 131.862 - Plux: € 11.450 - VirtuaGym: € 79.600
Project 5	**Personnel positions:** *- 1 PhD(1.0fte): € 191.364* **Consumables:** *€ 55.000* **Travel abroad:** *€ 8.000* **Investment:** *€ 0*	**In cash:** - 2M Engineering: € 20.000 - Innosportlab Sport & Beweeg: € 20.000 **In kind:** - 2M Engineering: € 20.600 - Innosportlab Sport & Beweeg: € 20.170 - Golazo Sport SX: € 20.690 - Gemeente Eindhoven: € 12.540
Project 6	**Personnel positions:** *- 1 PhD(1.0fte): € 191.364* *- 1 PhD(1.0fte): € 191.364* *- 1 PhD(0.2fte): € 38.273* **Consumables:** *€ 65.000* **Travel abroad:** *€ 20.000* **Investment:** *€ 0*	**In cash:** - KNVB: € 80.000 **In kind:** - KNVB: € 101.200 - Inmotio: € 21.800 - KNHB: € 40.072
Project 7	**Personnel positions:** *- 2 PhD(1.0fte): € 382.728* *- 1 NWP(0.8fte): € 56.362* *- 1 PDEng(1.0fte): € 87.540* **Consumables:** *€ 87.500* **Travel abroad:** *€ 24.000* **Investment:** *€ 0*	**In cash:** - Plux: € 27.000 - Motekforce Link: € 70.000 - ManualFysion: € 10.000 **In kind:** - Plux: € 11.450 - Motekforce Link: € 21.800 - ManualFysion: € 70.421 - KNLTB: € 65.400 - KNBSB: € 38.700 - ITF: € 13.000

Project 8	**Personnel positions:** *- 1 PhD(1.0fte): € 191.364* *- 1 PhD(0.5fte): € 95.682* *- 1 NWP(0.1fte):€ 19.097* *- 1 PD(1.0fte): € 126.432* **Consumables:** *€ 52.500* **Travel abroad:** *€ 16.000* **Investment:** *€ 0*	**In cash:** - Team Sunweb: € 10.000 - Reade Rehabilitation: € 40.000 - IZI Body Cooling: € 15.000 - NOC*NSF: € 15.000 **In kind:** - Team Sunweb: € 32.700 - Reade Rehabilitation: € 40.400 - Watersportverbond: € 20.000 - Sailing Innovation Centre: € 20.100 - MyTemp: € 20.440 - IZI Body Cooling: € 40.520 - NOC*NSF: € 66.400
Project 9	**Personnel positions:** *- 1 PhD(1.0fte): € 191.364* *- 1 PhD(0.5fte): € 95.682* *- 1 PD(1.0fte): € 190.980* **Consumables:** *€ 77.500* **Travel abroad:** *€ 24.000* **Investment:** *€ 0*	**In cash:** - Koninklijke Gazelle: € 80.000 - Bosch: € 40.000 **In kind:** - Team Sunweb: € 63.350 - Koninklijke Gazelle: € 28.642 - Bosch: € 96.000 - SWOV: € 20.000
Total	*€ 4.786.324*	**In cash:** *€ 786.324* **In kind:** *€ 1.777.727*

- WP = Other scientific personnel, including additional researcher, holders of a Master’s degree, medical graduates.
- NWP = Non-scientific personnel, including technical assistant.

8. Description of the projects in the program

For references, please see Section 9.3 (Appendices).

Project P1. Sensor Technology for unobtrusive athlete monitoring

Project leader: Prof. dr. W.A. Groen (TUD)
Co-applicant(s): Prof dr. P.J. French; Dr. A. Bossche; Dr. J.C. van Gemert (TUD-EWI); Dr Santiago J. Garcia (TUD-Aerospace Engineering).
Requested research positions: Scientific: 1 PhD (100% @ AE); 1 PhD (80% shared with P6); 1 PhD (50% shared with P8); Non-scientific: Engineer (50%, 24 month)
Budget: **Requested from NWO-domain TTW:** k€ 548 713
Contribution by users: k€ 110 000 (in cash) & k€ 295 440 (in kind)
Duration of project: 5 years

I Scientific description of the project
In this project we will develop technology to acquire physiological information of athletes in action through low-cost unobtrusive sensing. This is essential to all other projects (P2-P9_ as they all build on sensor information. Two monitoring methods will be used:
- Video sensing, where new computer vision methods will be developed to detect not only limb movement and acceleration but also tiny muscle movement, behaviour, and emotional state. The main scientific challenge is how to obtain accurate measurements from unconstrained RGB videos. This will be carried out in close cooperation with P4, P5, and P8.
- On-body sensing, where multi-sensor modules will be developed that can be embedded in sports clothing and operate in a self-powered, reliable and unobtrusive manner. This work will be carried out in cooperation with P5 and P6.
Combining the complementary on-body sensors with video sensing unlocks a wealth of data about athlete motion, condition and performance. The data fusion method is used in P2 and P3.

I·a Scientific challenge

- Unlock video sensing methods for realistic, unconstrained sport videos.
- Realize wearable sensors that are flexible and stretchable to be integrated in textile.
- Let sensors handle an aggressive environment (mechanical deformation, sweat, detergents).
- Realize robust energy harvesting based on stretchable piezoelectric materials.
- Unobtrusively embed and interconnect sensors and electronics on textile in a reliable manner.

I·b Methods
Approach: The project will start with inventorying consensus about the measurement requirements; what should be measured and with what accuracy and rate? We will follow a modular, multi-stage approach. First, a version-0 (v0) based on existing technologies will be created to quickly supply the partner projects with measurement means. Subsequently, new versions v1 and v2 will be developed to incorporate the newly developed technologies at more advanced integration levels.
State of the art starting points: <u>Video</u> <u>sensing:</u> A good coach can read his or her athletes like a book. An athlete's physical and mental state can be visually observed by facial expressions, pose, gait, speed, and behavior. Here, we aim to automatically extract the relevant visual cues from unconstrained video. Tiny motions [Wu (2012)] and accelerations [Zhang (2017)] can be obtained from video and the deep learning revolution makes it possible to extract facial expressions [Dibeklioglu (2017)], emotion [Khan (2017)], pose [Toshev (2014)], gait [Yu (2017)], and behaviour [Wang (2016)] with near-human accuracy from images. Where current methods work well in a lab setting, we will extend such methods to realistic video, which we will record and annotate. We will place cameras at fitness equipment (P4) and use videos recorded by MyLaps on runners with a unique ID on their bib

(P5). This will track athletes over time, and investigate which visual measurements are essential to performance and injury.

Wearable sensors: Recent on-body sensors for biochemical components, such as-lactate, glucose and also a number of other parameters [Brand, Poh and Gao] are based on enzymatic reactions [Rattee (2016)] which largely limit their lifetimes to days or mostly weeks. In this project we will focus on sensors based on physical principles (e.g. optical) that have unlimited lifetime [Tanase, (2001)]. Some examples of optical measurements of glucose and lactate can be found in [McNichols (2000), Tamada (1995), Marwin (1998), Marquette (1999)]. However, these methods were not built into flexible substrates and would be too bulky to fit into clothing. This will be the first devices to integrate and other (e.g. temp, heart rate, hydration), sensors into clothing with power and communication. To achieve this, sensor modules (<1mm) need to be integrated into a stretchable polymer, which also contains the interconnects. For the movement sensors we will focus on the same type of stretchable piezoelectric materials as will be used for energy harvesting. A novel lactate sensor will be combined with other sensors into a flexible substrate.

Energy harvesting from mechanical vibration offers an interesting option, especially in the field of sport where movements are essential. Traditionally, piezoelectric ceramics materials (PZT) are used. Disadvantages of these materials are their brittleness and toxicity (lead). PVDF, a fluorine-containing polymer has a limited temperature stability which makes integration into products difficult and their life time is limited. Our previous initial research yielded composites with an alternative (lead-free) filler material. These materials are very promising for environmentally friendly energy-harvesting applications. We aim to bring this technology into real-life applications in the field of sports.

Hardware integration will integrate the technology, i.e. embedding and interconnecting sensors and electronics on textile in an unobtrusive and reliable manner. The last decade, a lot of research [Prakazad (2012)] has been done on stretchable electronics. Some of these methods and materials have already become commercially available now (Dupont stretchable ink PE873/PE773). Non-trivial engineering problems are still to be solved to combine the different technologies. This task will be performed by an engineer (50%) in cooperation with the industrial partners.

I·c Time plan and division of tasks

	Members Involved									Link to program	2018				2019				2020				2021				2022			
	TUD-EWI-ME	TUD-AE	TUD-EWI-IS	Adidas	Motek	Nedcard	Mylaps	Novisense	Borre		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
WP1 Technology development																														
1.1 PhD1 : Wearable Sensors	X	X						X	X	P6, (P5, P7)		v0					v1					v2								
1.2 PhD2 : Energy Harvesting	X	X		X						P5, (P6, P7)																				
1.3 PhD3 : Video sensing methods			X							P8, (P4, P2)		v0					v1					v2								
1.4 Eng1 : Sensor Module Integration	X	X						X	X	P5,P6 (P7,P8)		v0					v1					v2								
WP2 Technical and experimental validation																														
2.1 PhD1 : Wearable Sensors Testing	X	X		X	X	X		X							v0					v1				v2						
1.2 PhD2 : Energy Harvesting Testing	X	X																		v1				v2						
1.3 PhD3 : Video sensing validation			X		X		X								v0					v1				v2						
1.4 Eng1 : Sensor Module Evaluation (3 traps)	X	X		X	X	X		X	X						v0					v1				v2						
WP3 Dissemination																														
3.1 Quick wins	X	X	X									v0																		
3.2 Application with sport partners				X			X	X	X																					
3.3 Application with medical partners					X																									

PhD1: Wearable Sensors (80% shared with P6; industrial partners: Adidas, Motek, Nedcard, Noviosense, Borre)

In this task, novel sensors will be developed to measure important motional (e.g. joint bending) and physiological parameters (lactate, oxygen) in an unobtrusive and durable manner. These sensors will be combined with more conventional sensors in a multisensor module to be integrated in sports-clothing. Motek will couple the sensor information to their human body model software, enabling individualized calibration and integration of the sensors.

PhD2: Energy Harvesting (industrial partners: Adidas)

This task will comprise the development of energy harvesting devices that can be integrated in the sensor module to make it self-sustainable. Devices will be developed, integrated and evaluated.

PhD3: Video Sensing (50% shared with P8; industrial partners: Motek, Mylaps)

The aim of this task is to develop advanced video sensing methods and algorithms to measure limb movement, acceleration, tiny muscle movement, behaviour, emotional state and energy level.

Subsequently the methods will be applied and evaluated in real sport situations.
Eng1: Sensor Module Integration (industrial partners: Adidas, Motek, Nedcard, Noviosense, Borre)
This task will focus on functional integration of sensors and electronics on textile substrates. It comprises the development of electrodes, interconnect, readout electronics and data communication to the outside world. Eng1 supports PhD1 and PhD2.

II Utilisation

The results and knowledge of this project will be used by all other projects to acquire real-time data from athletes. The different industrial partners will gain by further developing their products and technologies. Adidas will use it to develop sports clothing with advanced sensing capabilities; first for the professional athletes after which it is expected to migrate to the amateurs as well, just like HR and GPS watches did. Nedcard can extend their packaging technology to highly flexible and stretchable substrates. Motek can feed and extend their models with more advanced real-time data. Mylaps will include the advanced video sensing methods to monitor athletes in massive sports events. Novisense will implement the acquired knowledge in future wearable sensor products. Borre will be able to take these devices and build them into textiles for fashion and niche markets. Furthermore, spin-off to other markets such as health can be envisaged as well.

II·a The problem and proposed solution

Problem and impact: There is a growing demand for means to monitor performance and condition of athletes in action and during recovery. Important reasons are the prevention of injuries and overtraining. This holds both for all athletes, the professionals as well as for the large crowd of amateurs. Measurements are the first step towards learning, growing, improving in a healthy, responsible approach.

Proposed Solution: Sensing methods will only be widely accepted when they do not hamper athletes' performance or perception. Therefore this project aims to develop sensing methods that are unobtrusive, self-sustaining, have a long lifetime and do not require any special attention from the athlete. The ultimate aim is to build the sensor systems into clothing (with power and communication systems), which will be augmented with external video systems.

II·b In-kind contributions of users

Adidas will provide facilities and will help in prototyping of the apparel with integrated sensors. Novisense brings in knowledge on biosensors and makes existing sensors available for experiments and support the development of new devices. Mylaps will bring in their data and expertise for video sensing in large sports events and will support the development and implementation of advanced video sensing methods. Borre will support the development of textile with integrated sensors. Motek will couple the sensoric information to their real-time musculo-skeletal model which will enable real-time analysis and feedback to individual athletes. NedCard will make its technology available to properly package and seal the electronic components and sensing devices in order to protect them from the harsh and corrosive environment.

III Intellectual property

III·a Contracts

There are no contracts which will interfere with this project.

III·b Patents

There are a number of patents covering wearable sensors (e.g. US 5605152 A, US 2010/0252430A1). Our approach is to develop autonomous, communicating sensor systems in clothing with long-term reliability/stability. The system will be augmented with video sensing. To our knowledge there are no existing autonomous integrated sensor systems able to achieve this.

Project P2. Data science for injury prevention and performance improvement

Project leaders: Prof. dr. J.N. Kok (LEI); Prof. dr. ir. G. Jongbloed (TUD).
Co-applicant(s): Dr. A.J. Knobbe (LEI); Dr. ir. F.H. van der Meulen (TUD).
Requested research positions: 2 PhDs (one PhD with P4, 0.5 fte), 1 Postdoc (1 fte, 2 years), 1 Scientific Programmer (0.5 fte, 4 years)

Budget:	**Requested from NWO-domain TTW:**	€ 454 270
	Contribution by users:	€ 100 000 (cash) & € 62 080 (in kind)
Duration of project:		5 years

I Scientific description of the project

This project aims at providing a data-based tailored advice for health and performance. For every individual, a personalized model is tuned allowing for tailor-made advice. This model uses historic data of the individual athlete, such that it can incorporate information about how the athlete has responded to various training stimuli in the past, besides group information about comparable athletes. Moreover, the advice is adapted after every event and change in conditions (like a car navigation system that will update the calculated route depending on the traffic).
In this data-science project, data of various types and origin are used to support decisions in real time. To set up a real-time decision-support system for optimizing future performance and injury characteristics, it is decisive to first formally quantify what exactly is meant by *training load* and *status/performance* of an individual and how these concepts are related to (potentially) available data. The quantification of these concepts will depend on the particular sports. Therefore, close collaboration with the applied projects (P4-P9) is needed to arrive at the right choices. As regards to the data, different sources can be discerned, i.e.:

- Loading data obtained on individuals from various types of sensors (P1);
- Data about physical status obtained from questionnaires, apps voluntarily entered by participants;
- Data shared by multiple individuals simultaneously, such as environmental factors.

From these data sources, both historical and real time measured data can be used.
While high-frequency sensor data have the potential to take individual-specific characteristics into account, in practice such data can be noisy and correlated. Data that are shared across individuals may provide further information on the status of individuals. A key idea in the analysis of the data is that data associated to individuals with similar characteristics may help predicting each other's future risk of injury, a concept known as *borrowing strength* in the statistical literature. It is one of the research goals to apply this idea to the case where different data sources contain measurements at different time scales and levels of accuracy. For decision support, one wishes to model the probability of injury (or expected increase of performance) under different future (training) scenarios. Our aim is to define statistical models that incorporate the different data sources and sports-dependent available models (P6 e.g. muscular skeleton; P4 physiological) while maintaining tractability. The latter is important, because the model has to be *tuned* to the data.

I·a Scientific challenge

Currently, data are often used subjectively to decide to change a training schedule, either to increase performance or prevent injury. There is a need for more objective use of the data to support decisions on modifying the schedule, also borrowing strength from others. The available data originate from various sources with associated quality, time scale and structure. Integrating these data with domain knowledge asks for the development of new methods and models to feed these ingredients into real time personalized advice for the athlete. Output of these models needs to be presented to the athlete visually and easy to understand, which is the focus of P3. The main challenge is to develop individual prediction models with regard to injury, performance and motivation of athletes by establishing the relationship between (to be) measured physical activity and those variables (properly quantified). This relationship will be established by first exploring large data sets and then tuning the resulting general performance models to individuals by utilizing individual-specific data. Information will be produced in real time, which opens up possibilities for new feedback applications like apps, avatars and virtual

coaches to be developed in P3 and tested in the applied projects P4-P9.
The biggest challenges lie in creating: (1) models that adapt to changing circumstances real time, comparable to the way car navigation systems adapt the route and the estimated time of arrival based on the amount of traffic; (2) individual and tailored prediction models on injury risk and performance for specific user groups.

The project goal is to turn heterogeneous data from various sources into personalized training advice, improving performance and minimizing risk of injury.

I·b Methods

Approach: First, quantification of performance and risk of injury based on domain knowledge will be pursued (P4, P6, P7, P8). Then, measurable quantities related to these entities will be identified and measured (P1) or are derived from already collected data. Relations between the quantified entities and measured quantities will be modelled and parameters tuned (both individual as group wise) also taking domain-specific models into account.
State of the art starting points: Modelling and analysis of time-to-event data is a solid area within the field of statistics. Domain-specific models (muscular skeleton, physiological,..) are also available as well as a critical amount of relevant data (especially from running, fitness and tennis).

I·b Time plan and division of tasks

PhD1 will determine indicators related to performance and injury within various projects (P6, P7, P8). Also, informative measurements and characteristics of the measuring devices will be studied. The relations of the measured quantities and performance (risk) indicators will be modelled. Models will be constructed translating the data into personalized advice (P1, P6).
PhD2 will focus on data from fitness centres and take care of the modelling part, also using the initial results of PhD1 for fitness specifically. A feedback system will be built. Experiments will be performed to validate the model (e.g. which information is relevant and which is not?) and feedback. Joint position with P4.
PD will focus on data from elite sports, focussing the first year on cyclic sports and the second year on team sports. Performance and injury risk in cyclic sports depend on individuals, while in team sports individual models of players need to be combined for finding models for the “performance” and “injury risk” of a team as a whole. Connection to P6, P7 and P9**.**
SciPro will be responsible for the data infrastructures in the entire project by acting as a CDO (Chief Data Officer) and also construct programs needed for the data analysis and visualizations.

II Utilisation

II·a The problem and proposed solution

Problem and Impact: In sports, a large number of parameters of training schedules need to be tuned to the specific physique and circumstances of a given athlete. Extensive analysis of historical data (on individual and large scale) can help to optimise these parameters, and how possible pitfalls of under- and overtraining in the past can be avoided in the future. Both athletic performance and an athlete’s health are affected by loading of the athlete’s systems. The fine balance between load capacity and loading determines whether exposure to training stimuli affects performance positively and whether physical and psychological health is not negatively affected (e.g. through injury, overreaching, or illness). More into the future, we expect many people (in a sporting situation or not) to take real-time measurements on their condition and share these. At a larger scale, the methods to be developed in this project can then be applied to give personalized advice to these people regarding issues of health and performance.
Proposed Solution: We intend to discover interpretable and easy-to-understand patterns that ideally do not involve too many variables. Assuming mostly linear dependencies between the features and the target variables, regularised (local) linear regression is attractive. However, within the physiological one can expect non-linear dependencies. There will be close interaction with domain experts (physiologists, coaches, athletes) on which variables to measure and relations / restrictions to use in the models. The aim is to provide the coaching staff / athlete with actionable pointers as to how to tune the training routines, and avoid pitfalls of under and over-training.

II·b In-kind contributions of users

Nationwide, in fitness centers, data are continuously being collected and (subsets) of these collections are available for the project. Moreover, MyLaps will contribute in kind (80k€) through expertise and making its data collections available for the project. KNLTB also contributes in kind (21,8k€), through data availability, interpretation and algorithm development.

III Intellectual property

III·a Contracts: No contracts.

III·b Patents: Patenting is not customary in this branch of research.

Project P3. Personalized feedback that works

Project leader: Prof.dr. Peter J. Beek (VU)
Co-applicant(s): Prof.dr. Catholijn M. Jonker, Dr. Stephan Lukosch (TUD)
Requested research positions: 1 PhD (1.0 fte), 1 PhD (0.5 fte, shared with P9), 1 PDEng (1.0 fte, 24 months).

Budget:	**Requested from NWO-domain TTW:**	€ 374 086
	Contribution by users:	€ 66 500 (in cash) & € 230 000 (in kind)
Duration of project:		5 years

I Scientific description of the project

Feedback about one's performance is not only a *sine qua non* for motor control, learning and training, but also for stimulating people to engage in and sustain physical exercise in a safe and healthy manner. Besides inherent feedback, i.e. sensory information that is a natural part of performing a skill or activity, augmented feedback, i.e. performance related information added to or enhancing inherent feedback, plays a crucial role in this regard.[1] Despite the vast literature on feedback and motor learning, it is still largely unknown what the optimal feedback is to improve performance in a safe and healthy manner, and how to deliver this feedback. Particularly now that wearable sensors are taking the world of sports and exercise by storm, generating a wealth of data, and mixed reality environments are rapidly gaining ground, the quest for optimal feedback solutions is more pressing than ever before. If successful, the present project will enrich current technologies and ignite new technological developments for performance improvement and injury reduction in sports.

I·a Scientific challenge

Recent technological advances and feedback solutions have not been (or are seldom) based on current insights into perceptual-motor learning and intervention methods with proven effectiveness.[2] In general, it is known that motor performance and learning benefit greatly from positive feedback and expectancies, intrinsic motivation, personal autonomy and information that couples actions to goals.[3] The challenge addressed in this project is to bridge the gap in current feedback solutions between wearable sensor, mixed reality and data science technology on the one hand, and evidence-based insights into effective conditions of behavioral change and perceptual-motor learning on the other hand. By bridging this gap, new technological devices can be developed that provide optimal feedback thus increasing their appeal from a user and a commercial perspective. This requires that the aforementioned behavioral knowledge is implemented in new feedback solutions that are tested and evaluated in terms of their effectiveness, and conversely that technology is expanded for this purpose.

The project goal is to develop, test and implement novel feedback solutions that effectively achieve lasting changes in behavior associated with both performance and health goals.

I·b Methods

Approach: Established principles of motor learning will be translated to and implemented in dedicated feedback solutions in specific sports domains and their efficacy will be compared to existing solutions. In particular, we will develop, test and implement feedback solutions that (i) highlight performance improvement to enhance the user's expectancies and self-esteem, (ii) exploit elements of gaming and interaction with peers to enhance the user's motivation, (iii) allow for self-selected, personalized feedback to enhance the user's senses of autonomy and accomplishment and (iv) elucidate the coupling between movements and goals to allow the user to actually make the required technique improvement. This work will be done in close interaction with the applied projects P4-P9. The aforementioned principles will be implemented and tested using easy-to-wear feedback devices, such as headphones or head-mounted devices, augmenting the user's environment. Figure 1 shows artist renderings of such augmented reality feedback provided to athletes in three different user cases.

a) Fitness (P4) b) Running (P5) c) Cycling (P9)

Figure 1 Examples of augmented reality feedback.

State of the art starting points: Feedback systems for strength training and fitness are still in their infancy, but Moterkforce Link's Full Body Model provides a starting point for building a feedback environment in this context. CINOPTICS monocular head-mounted device SMART-EYE provides a basis for providing visual feedback to athletes. We recently developed a model for estimating the optimal stride frequency for a given running speed, allowing us to provide feedback on running technique besides quantitative aspects like speed and distance covered. Likewise, for baseball pitching a biomechanical model has been developed on the basis of which a feedback environment can be designed. A similar situation exists for maintaining balance and descending in cycling. Publications about these modeling results are currently in preparation.

I·b Time plan and division of tasks

The PhD students and the PDEng in the project will have the following tasks:

<u>PhD 1: Evidence-based feedback mechanisms</u>

PhD 1 will develop and validate feedback mechanisms for selected sports from the applied projects P4-P8 relying on evidence-based motor control and learning principles.

<u>PhD 2: Cycling feedback mechanisms (50%, shared with P9)</u>

PhD 2 will develop and validate an augmented reality feedback environment for elite road cycling.

<u>PDEng: Software applications and integrated systems</u>

The PDEng supplied by Noldus will develop software for the provision of feedback on mobile and wearable devices using a generic messaging framework that will be widely applicable.

	VU-MOVE	TUD-EWI-II	TUD-TPM-SE	Noldus	Dopple	Cinoptics	twnkls	Link to program
WP1 Technology development								
1.1 Messaging framework for feedback mechanisms (PDEng)	x	x	x	x				
1.2 Evidence based feedback mechanisms (PhD1)	x		x		x		x	P4-P8, WP1
1.3 Feedback mechanisms for cycling (PhD2)		x	x			x	x	P9, WP1
WP2 Technical and experimental validation								
2.1 Validation of messaging framework (PDEng)	x	x	x	x				
2.2 Validation of evidence-based feedback mechanisms (PhD1)	x		x		x		x	P4-P8, WP2
2.3 Validation of cycling feedback mechanisms (PhD2)		x	x			x	x	P9, WP2
WP3 Dissemination								
3.1 Application of evidence-based feedback mechanisms	x		x		x		x	P4-P8, WP3
3.2 Application of cycling feedback mechanisms		x	x			x	x	P9, WP3
3.4 Transfer of feedback mechanisms to other sport domains	x	x	x	x	x	x	x	P4-P9, WP3

	2018				2019				2020				2021				2022			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
WP1 Technology development																				
1.1 Messaging framework for feedback mechanisms (PDEng)			v0			v1														
1.2 Evidence based feedback mechanisms (PhD1)			v0			v1				v2				v3						
1.3 Feedback mechanisms for cycling (PhD2)			v0			v1				v2				v3						
WP2 Technical and experimental validation																				
2.1 Validation of messaging framework (PDEng)				v0			v1													
2.2 Validation of evidence-based feedback mechanisms (PhD1)				v0			v1				v2				v3					
2.3 Validation of cycling feedback mechanisms (PhD2)				v0			v1				v2				v3					
WP3 Dissemination																				
3.1 Application of evidence-based feedback mechanisms								v1				v2				v3				
3.2 Application of cycling feedback mechanisms								v1				v2				v3				
3.4 Transfer of feedback mechanisms to other sport domains												v2				v3				

II Utilisation

The present project is of relevance for the applied projects P4-P9. The activities within this project will be aligned with the aims of P4-P9 from the start and developed further as the CAS program unfolds.

II·a The problem and proposed solution

Problem and impact: To achieve the goals of the CAS program, it is necessary to enrich and infuse feedback technology with knowledge about human motor behavior, which thus far has hardly been the case, leaving the full potential of current technological advances untapped. The project results will lead to innovations in the products of the participating companies, giving them a competitive edge.

Proposed solution: Enriching and infusing the emerging technology-based feedback solutions in the domain of sports performance and injury prevention with scientifically established knowledge about (optimal conditions for) training, motor learning and behavioral change will make those solutions more effective in achieving their objectives and add to their individual, societal and commercial value.

II·b In-kind contributions of users

Cinoptics, a company specialized in high-end Head Mounted Displays (HMDs) for virtual and augmented reality applications, will contribute maximally 192 hours of a senior engineer to customize and adapt the company's hardware to meet specific project requirements.

Noldus will contribute in total 1518 hours of a senior system engineer, software engineer and advisor for the development of software for continuous, longitudinal monitoring of human activity as well as the development of a messaging framework.

Dopple B.V. is a newly established company that focuses specifically on the development of small, low power, wearable and wireless products for music, voice and sensor applications. Dopple supports the research on effective audio feedback solutions and will contribute €2500 worth of equipment, 300 hours of a senior engineer and 300 hours of technical staff.

Twnkls b.v. is a Dutch company specialized in augmented reality software. TWNKLS contributes a maximum of 190 man-hours of a senior engineer over the course of four years to customise and adapt their software on racking & recognition and outdoor navigation to meet specific project requirements.

III Intellectual property

III·a Contracts

There are no contracts with third parties that will interfere with the present project.

III·b Patents

While there are no restrictions to utilize the results of the proposed research activities, there will be ample opportunity to exploit those results in product development.

Project P4. Show your muscles! Fitness & strength training

Project leader: Prof.dr. Frans C.T. van der Helm (TUD)
Co-applicant(s): Prof.dr. H.E.J. Veeger (VU/TUD), Prof.dr. D. Eygendaal (AMC), Dr. B. Visser (HVA)
Requested research positions: PDeng (100%, 2 yrs), PhD1 (1.0 fe), PhD2 (0.5 fte, with *P2*), Casimir PhD (0.5 fte, 3 yrs)
Budget: **Requested from NWO-domain TTW:** € 510 835
Contribution by users: € 82.824 (in cash) & € 283 812 (in kind)
Duration of project: 5 years

I Scientific description of the project

I·a Scientific challenge

With 3.1 million participants fitness and strength training belong to the largest sports and exercise domains in the Netherlands. Annually 370.000 participants (i.e. 12%) become injured, out of which 150.000 seek medical treatment, which ranks fitness and strength training on the third place of injury-prone sports behind football and running, with the upper extremity (24%) and the back (14%) as the most injury-prone areas. Injuries occur at all training levels, ranging from novice recreational athletes to elite athletes. In spite of the aforementioned injury prevalence, injury mechanisms and their relation to the load on the musculoskeletal system are unknown, making it hard to propose effective injury prevention measures. The dropout rate of recreational athletes is quite high and might be reduced by stimulating feedback about (increasing) performance levels, personally adjusted training schemes and injury prevention. An important issue in this context is the 'return to sport' after injury, surgery, or trauma. Where personally adjusted training schedules are useful for injury prevention, they are indispensable following an injury (see also P7). This requires feedback systems that are modified based on personal injury specifics and rehabilitation aims.

The project goal is to develop real-time feedback systems using musculoskeletal models, providing information on muscle load that enables recreational, elite and rehabilitating athletes, to optimize their training schedule and load based on personal characteristics.

The major challenges are:

- Developing instrumented devices recording the loading on athletes, in combination with affordable camera systems that are still able to accurately reconstruct the 3D motions.
- Using load and motion recordings to calculate muscle loading using individualized musculoskeletal models.
- Deriving information about physical status using camera systems measuring facial expressions and physical information like heart rate, skin color and sweat.
- Combining muscle loading, physical status and injuries to assess injury mechanisms.
- Combining musculoskeletal models and muscle feedback systems based on EMG to provide detailed and fast muscle coordination feedback.
- Providing feedback to prevent injuries and improve the way to execute exercises.

I·b Methods

PDeng (TUD/Motekforce Link): Since most fitness devices are stationary, it is relatively simple to equip these devices with force sensors and motion capture cameras like Kinect, in order to measure the actual external load. The PdEng will also connect the output of the Delft Shoulder and Elbow Model to the Human Body Model, so as to provide real-time feedback.

PhD1 (TUD): The Delft Shoulder and Elbow Model (TU Delft) will be used to estimate the required contribution of muscles and load in joints (internal load) related to that external load. A set of maximal force measurements using a static force transducer can be used to scale the muscle strength to the individual athlete (Bolsterlee et al., 2015). Human Body Model (HBM; Motekforce Link) can use the moment arms and muscle strength to generate an individualized real-time model. Using the recorded external forces and joint angles, the HBM can display a muscle avatar to show the active muscles, providing feedback about the correct execution of the motion to prevent injuries, and about the performance. An app with a daily questionnaire will be used to obtain information about the health status of the athlete (VirtuaGym). To calculate loads in case of 'return to sport' after injury, HBM requires additional information on unwanted muscle activation or disuse. Simple muscle recording systems (Plux Go, Plux) will be integrated with the HBM pipeline to track and monitor load changes related to changes in muscle coordination, focusing on rehabilitation.

Casimir PhD (TUD/Noldus) will explore the possibilities to obtain the current physical health status, now volitionally entered offline through a questionnaire by app (VirtuaGym), by measuring facial expressions and physical information. FaceReader software from Noldus IT B.V. analyses facial features, and combines these features into emotions. The facial features and/or emotions will be combined with motions and physical information also obtained by camera systems, such as heart rate, sweat, skin color. Machine learning techniques will estimate the perceived loading.

PhD2 (with P2 (TUD/LUMC)) will generate models about injury mechanisms, using the health status and muscle loads from HBM. Providing information using apps about muscle forces is presumed to be an incentive to the participants to keep exercising, whereas advise can be given about the proper motion execution, load and number of repetitions to prevent injuries (VirtuaGym). In collaboration with VirtuaGym the PhD2 will start his analysis using newly acquired data by the current app as been marketed by VirtuaGym, reaching out to about 25% of the fitness athletes.

I·b Time plan and division of tasks

	Members Involved										Link to program
	TUD-3mE-BMechE	VU-HMS	HvA	Motekforce Link	Noldus IT b.v.	Watersportverbond	Sailing Innovation Cent	VirtuaGym	Fit!Vak	Plux	
WP1 Technology development											
1.1 Pdeng (motion acquisition / HBM)	X			x				x	X		P1
1.2 PhD1 : Musculoskeletal modelling	X	X		x		x	x	x	x	x	P2,P3
1.3 PhD2 (0.5fte, P2): Data Science	x			x				x	x		P2
1.4 Casimir PhD : physical status Face Reading	X				x			x			P1,P3
WP2 Technical and experimental validation											
2.1 Pdeng (implementation motion acq./ HBM)	X			x				x	X		P7
2.2 PhD1 : test individual Musculoskeletal modelling	X	X	x	x		x	x	x	x	x	P7
2.3 PhD2 (0.5fte, P2): apply algorithms for indiv.	x			X				x	x		P2
2.4 Casimir PhD : test algorithms	X				x			x			P1,P3
WP3 Dissemination											
3.1 Quick wins	X	X	x	x	x						
3.2 Application with sport partners				x	X	x	x	X	X		
3.3 Application with medical partners				x	x					x	

II Utilisation

II·a The problem and proposed solution

Problem and Impact: As indicated, injuries are a common but easily overlooked problem in fitness and strength training about which little is known. From a web questionnaire of the Injury Information System (BIS) it appeared that wrong exercise execution, fatigue and joint strain are the main causes of injury. Furthermore, more than half of the participants do no warming-up or cooling-down. It was suggested that many injuries can be prevented by better supervision and instruction.

There is a demand for more and better information in order to prevent injuries and to return to sport after injury. The participants should be tempted to provide information about their physical status in return for feedback about performance, personalized instruction and injury risk.

Proposed Solution: Since most fitness devices are stationary, it is relatively straightforward to equip the devices with force sensors and motion capture cameras (Motekforce Link), to measure the actual load. Extraction of facial information to estimate the perceived load (which includes the physical status of the athlete) is novel, and will be combined with physical information (heart rate, sweat, etc.) captured by camera systems (Noldus IT b.v.). Providing information using apps about muscle forces is presumed to be an incentive to the participants to keep exercising, whereas advise can be given about the proper motion execution, load and number of repetitions to prevent injuries (VirtuaGym). Modern exercise facilities will increase the attractiveness of fitness centra (Fit!Vak). The research program will focus on strengthening exercises for top and recreational athletes (Watersportverbond), and also for rehabilitation or the training of specified coordination patterns (Plux).

II·b In-kind contributions of users

Motekforce Link is a company in rehabilitation technology, very strong in research and together with their Chinese partner DIH one of the largest companies in the field worldwide. It has the intention to build instrumented exercise devices and is willing to share the Human Body Program (HBM) for this project. HBM is a real-time musculoskeletal model, which will be personalized to each participant, with a nice user-interface. Motekforce Link will have an in-kind contribution to individualize HBM for each participant, and connect it real-time to camera information and force sensors.

Noldus IT b.v. will assist in providing their facial recognition software and expertise, and integrate this with physical information obtained from camera systems.

VirtuaGym is selling apps with individualized exercise programs. VIrtuaGym will include the overwhelming information about muscle forces in new apps, focusing on proper user interfaces, including advise about potential overload and injury prevention.

Fit!Vak is the branch organization of fitness centres with more than 200 members, interested in the market potential of newly instrumented exercise devices.

Watersportverbond and **Sailing Innovation Center** will advise about the specific information required by top athletes interested in strengthening programs to improve their highly competitive performance.

Plux is specialised in muscle feedback systems, focusing on muscle coordination. They will support the development of the link of their system to DSEM/HBM and provide their Plux Go at reduced cost.

III Intellectual property

III·a Contracts

There are no contracts with third parties that will interfere with this project.

III·b Patents

While there are no restrictions to utilize the results of the proposed research activities, there will be ample of opportunities to exploit those results in product development.

Project P5. Run-Work-Sleep-Repeat: 24/7 monitoring for healthy running

Project leader: Prof. dr. S.B. Vos (TU/e & Fontys Univ. of Applied Sciences)
Co-applicant(s): Prof. dr. ir. A.C. Brombacher (TU/e), Dr. E. Verhagen (VUmc)
Requested research positions: 1 PhD (1.0 fte)

Budget:	**Requested from NWO-domain TTW:**	€214 364
	Contribution by users:	€40 000 (in cash) & €74 000 (in kind)
Duration of project:		5 years

I Scientific description of the project

In this project we aim to support people in achieving an active and healthy lifestyle through injury-free running. At the moment, real life 24/7 monitoring systems are not available on the consumer market.

I·a Scientific challenge

In this project, a data-driven and data-enabled design and research approach will be applied to tackle the following challenges:

- To merge conventional sensor electronics (measuring parameters related to an active and healthy lifestyle) with industry-ready, mass-producible, intelligent, but still washable fabrics. The key challenge here is to find an optimal solution balancing seamless and unobtrusive sensor integration, reliability of information and low-cost sensors, which allow to address the large group of people targeted in this project.
- To assess the total (training) load of recreational runners through 24/7 monitoring in real-life situations using low-cost sensors for running-related parameters (intensity based on heart rate and speed), posture, perceived intensity of the running sessions (through an app) and healthy lifestyle-related parameters (physical activity, sleep and stress). These parameters give insight into the health condition of a person.
- To determine through data modelling, (i) the interaction between running related parameters, daily-life patterns and health status, and (ii) on an individual basis, the optimal sports-life / load-balance in relation to the prevention of overuse injuries.

One PhD student will be involved in this project. He/she will be supervised by the applicants and will receive support by postdocs involved in P1 (sensors and energy harvesting), P2 (data science) and P3 (feedback systems).

The project goal is to design an unobtrusive 24/7 monitoring system which is able to measure a personal workload profile related to running and healthy lifestyle parameters.

I·b Methods

Approach: The new system will provide feedback about the right amount of activity at the right time using the right message. Obviously, this requires a close collaboration with P1, P2 and P3. The combination of running-related parameters (intensity based on heart rate and speed, posture and perceived intensity of the running sessions through an app) and healthy lifestyle-related parameters (other physical activities, sleep and stress) will result in personal (work)load profiles which are used to provide feedback and advice on the training sessions (Vos et al., 2016). Signal processing is used to interpret the 24/7 monitored data and create valuable and insightful feedback.

In **experiment 1**, which will involve 100 recreational runners, we will integrate data (among other means via Bluetooth) from separate low-cost off-the-shelf sensors (through an android prototype), which allow to determine and understand the interaction between running related parameters, and 24/7 healthy lifestyle-related parameters. An initial system will allow the data to be captured, processed and stored.

We will also make use of the 'risk of running-related injuries-model' developed by VUmc. This model allows for valid and reliable prospective registration of running related health problems through a translated and adapted Dutch version of the OSTRC Questionnaire on Health Problems. The model has been developed and evaluated in the HealthyMiles and HealthyTrails studies, and is currently being validated and modified to other sports modalities at elite and non-elite levels. This approach allows for long term tracking of health on a frequent basis, creating a data set with exposure and health problems without recall bias.

In **experiment 2**, which will be conducted in close collaboration with P2, we will venture to determine, through data modelling, the optimal sports-life / load-balance in relation to the prevention of overuse injuries for individual runners. The latter will be based on the ‘risk of running-related injuries-model’ developed by VUmc. The data gathered in experiment 1 will be used as a starting point for this study. In addition, an extra 100 runners will be included in this study.

In the **experiment 3**, in close collaboration with P1, an integrated and practical to use unobtrusive, full wearable solution for healthy and injury free running will be developed, merging conventional (sensor) electronics with, industry ready, mass producible intelligent fabrics. The representation of the feedback (tactile, visual, auditive) will be personalized through feedback systems (together with P3).

I·b Time plan and division of tasks

	Members Involved							Link to program	2018				2019				2020				2021				2022			
	TU Eindhoven	Vumc	Fontys Sporthogeschool	2M Engineering	Golazo Sports SX	Innosportlab Sport & Be	Gemeente Eindhoven		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
WP1 Technology development																												
1.1 Initial system for data acquisition through low cost senso	x	x		x				P1																				
1.2 Data analytics and optimal sports-life / load-balance mod	x	x		x				P2																				
1.3 Designing an unobtrusive full wearable solution	x	x		x				P1/P3																				
WP2 Technical and experimental validation																												
2.1 Testing the initial system	x		x		x	x	x	P1																				
2.2 Validation of the load-balance model	x	x	x					P2																				
2.3 Testing the unobtrusive werable solution	x		x		x	x	x	P1/P3																				
WP3 Dissemination																												
3.1 Quick wins (HBO instellingen)	x		x																									
3.2 Application with sport partners	x		x		x	x	x																					
3.3 Application with medical partners	x	x			x																							

II Utilisation

2M Engineering, as industrial partner, will utilize the foreground knowledge to further improve, in collaboration with the involved universities and Fontys University of Applied Sciences, their products and technologies related to the monitoring of sports and physical activity. Golazo Sports SX and InnoSportlab Sport & Beweeg, and the end-users they represent, can reduce drop-out in running by preventing overuse injuries using the developed 24/7 monitoring system. The city of Eindhoven will use the results of this project for their policies related to the support of sustainable running in urban areas.

II·a The problem and proposed solution

Running is one of the most popular forms of sports participation in Western Europe, with approximately 50 million participants (Breedveld et al., 2015). Running fits with our more dynamic and often less organized schedules and life patterns (Vos, 2016). Indeed, our current 24/7 economy puts constant pressure on a healthy and active lifestyle. Each individual has to combine the demands of family, with the demands of work, social life, leisure time, sleep, etcetera. Running offers opportunities for this growing group of ‘busy’ people to achieve an active and healthy lifestyle (Hespanhol et al., 2015; King et al., 2009). Yet, for less experienced runners, this often results in high drop-out rates due to injuries (e.g. Bredeweg et al., 2012; Hespanhol et al., 2016; Videbæk et al., 2015; Tonoli et al., 2010), lack of motivation and other constraints (Vos et al., 2016). Currently, runner’s make use of standardized training programs and / or advice, which don’t take into account the daily lifestyle and dynamics of runners on a 24/7 basis, for example, a stressful day at work, lack of sleep because of children, an unexpected game of squash with friends.

Unfortunately, (i) this kind of unobtrusive 24/7 monitoring device is not available on the consumer market, and (ii) the flood of data currently provided by many of the commercially available systems to users has not lead to substantial improvements with respect to sports-life balance, performance or reducing injury risk.

II·b In-kind contributions of users

The contribution of Golazo Sports SX (/20.690 € in kind) allows for the access to unorganized and less experienced runners through their mass running events and data bases. Via Golazo Sports participants will be recruited for the three studies mentioned above. InnoSportlab Sport & Beweeg contributes 20.000€ cash and 20.170€ in kind, making their field lab facilities available for testing the designed technologies in a semi-controlled lab setting. The city of Eindhoven will contribute 12.540€ in kind. They will make the Eckart and Genneper Parken areas available for testing the designed technologies in a real-life setting. The contribution of 2M Engineering (20.000€ cash / 20.690€ in kind) enables the merging of conventional sensor electronics with intelligent fabrics that reliably interconnect and / or sense at specific locations.

III Intellectual property

III·a Contracts: No relevant contracts.

III·b Patents: No relevant patents.

Project P6. Reducing hamstring injuries in soccer and field hockey using smart sensor shorts

Project leader: Prof. K.A.P.M. Lemmink (RUG)
Co-applicant(s): Prof. K.M.B. Jansen (TUD), Prof. G.J.P. Savelsbergh (VU), Edwin Goedhart (KNVB)
Requested research positions: 2 PhDs (1.0 fte), 1 PhD (0.2 fte, with P1)
Budget: **Requested from NWO-domain TTW:** € 426 001
Contribution by users: € 80 000 (in cash) & € 163 072 (in kind)
Duration of project: 4 years

I Scientific description of the project

Muscle injuries constitute more than a third of all time-loss injuries in soccer and field hockey and cause more than a quarter of the total injury absence, with the hamstrings and adductors being the most frequently involved (Ekstrand et al., 2016). Despite diverse efforts on prevention of muscle injuries, there is an annual increase of hamstring injuries in professional soccer and hockey. An important reason for this type of injuries is the high muscle stress during explosive actions like sprinting, directional changes, jumping and kicking in modern game-play (Barnes et al., 2014). However, the currently available monitoring systems are not able to measure the load of the musculoskeletal system around the hip.

The project aims at developing a system that is able to identify and monitor hip-related muscle stress. For this we will develop smart sensor shorts that can measure movements around the hip, process the data and transmit it to a laptop. Based on individual biomechanical models, a software tool will be developed, which enables the medical and technical staff to monitor the hip-related muscle stress of 10-20 players simultaneously during isolated actions as well as game-based training to guide the training process and signal overload.

The project contains three work packages taking care of sensor development and garment design (with P1), data handling, interpretation and implementation with the athlete's individual load/overload model (with P2) and the development and visualization of the monitored variables (with P3).

I·a Scientific challenge

The hip-related muscle groups are the most frequently involved in non-contact muscle injuries and appear mainly at the end of the first and second half of a game, indicating overload. To date there is a lack of knowledge concerning the assessment of sport-specific load of the hip-related muscles, leading to an inability to monitor and adjust load adequately. More specific, there is no real-time monitoring system that provides accurate information about hip movements of players during practice and match-play. The current standard is to track players general movements in the field based on positional information (x, y, z with GPS or LPM). This allows the calculation of distances, speed, directional changes and accelerations/decelerations, but the latter are measured at the location of the LPM or GPS module (mainly the upper back) and does not provide any specific information about limb acceleration forces during kicking, passing, sprinting and twisting, which are expected to be the main indicators for hip-related muscle injuries. Hip models for some isolated actions, like kicking, are available but hip models of different actions should be integrated to calculate muscle stress during exercise and training. In this project we focus on measuring local movements during isolated actions and game-based training by wearing sensor shorts and develop individual (over)load models that can be used to optimize performance and prevent hip-related muscle injuries (Nedergaard et al, 2017). Feedback will be provided real-time to the coach or physical trainer for multiple players simultaneously using an app and tablet.

The project goal is to develop novel, unobtrusive, low-cost smart sensor shorts to monitor real-time the individual hip-related muscle stress to optimize performance and prevent hamstring and groin injuries.

I·b Methods

Approach: In order to identify muscular stress indicators, data based on biomechanical models from the sensor shorts will be compared with data from accurate and validated 3D movement analysis methods indoor (VICON) and outdoor (LPM) (both available at the KNVB campus) during different activities (running, jumping, kicking, directions changes, etc.) and training games that involve healthy players and players in rehabilitation after hamstring injuries,.

State of the art starting points: Biomechanical models to calculate hip joint load and muscle stress have been documented for isolated explosive actions in soccer, like kicking and passing. Other models concentrate on knee load during sidestep cutting and jumping. However, validated models of isolated explosive actions in soccer and hockey, like sprinting and directional changes need to be integrated to develop a monitoring system of hip load and muscle stress during exercises and game-based training. Accelerometer based sensor systems, which monitor local bending movement were developed for rehabilitation training (Godfrey 2008, Patel 2012) but are too bulky to be used in the field, whereas optical motion tracking systems like Xsens require camera systems near the objects that is also not feasible in the field. Accelerometers, however, may be used for a zero version such that already early in the project movement data is generated.

I·b Time plan and division of tasks

	Members involved								Link to program	2018				2019				2020				2021				2022			
	Lemmink, RUG	Jansen, TUD-IO	Savelsberg, VU	Goedhart, KNVB	Bossche/French, TUD-E	InMotio	HvA	HAN		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
WP1 Technology development																													
1.1 Sensor development, version1, 2, 3 (PHD A)		X			X				P1	Sensor v1						Sensor v2					Sensor v3								
1.2 Data pre-processing and transmission (PHD A)		X			X				P1																				
1.3 Garment design v0-3 (PHD B)		X								Garment v0 (existing tec					Garment v1 (sensor v1)					Garment v2 (sensor				Garment v3(final)					
WP2 Technical and experimental validation																													
2.1 Testing and validation of garments (PHD B+C)	X	X	X										test G, v0					test G, v1					test G, v2			test G, v3			
2.2 Model of local hip movements, v1, 2, 3 (PHD C)	X		X						P2																				
2.3 Validation of model (PHD C)	X		X						P2																				
2.4 Data interpretation App v1, 2, 3 (PhD C)						X			P3																				
WP3 Dissemination																													
3.1 Quick wins (HBO instellingen)	X		X				X	X																					
3.2 Application with sport partners	X		X	X									test G, v0					test G, v1					test G, v2			test G, v3			
3.3 Application with commercial partners						X						App v1					App v2					App v3				dissem of App			

The tasks of the three PhD students involved are as follows:

<u>PhD A: Technology development</u> (20%, 80% P1)

New sensor shorts are developed which can measure local movement in hip joints as well as the positional displacements. The sensor shorts should be robust, low-cost, washable and preferable should pre-process the data before wireless transmission. Moreover, the garment(s) should be easy to put on and take off, should be comfortable and the sensors should not hinder physical activity.

<u>PhD B: Technical and experimental validation (100%)</u>

Positioning of the sensors should be based on comparison with validated models of hip load and muscle stress during isolated actions and game-based training. This PhD should also take care of the meaningful presentation of all monitored information in an easy to use overview. The programming of this interface will be in cooperation with P3.

<u>PhD C: Interpretation and validation (100%)</u>

For the real-time interpretation of the local movements, existing musculoskeletal models are not suited and new models will be developed and validated that can predict hip load and muscle stress real-time (together with P2). These predictions should take into account the differences in physical capacities of individual players and should be presented in an intuitive way.

II Utilisation

The newly acquired data will provide the medical and technical staffs of the KNVB and KNHB the opportunity to monitor the local load of the hip joint related muscular system during the different training drills and matches. This enables them to adjust the training loads if unwanted peak values appear. Therefore a necessary user-friendly interface will be developed. During rehabilitation the sensor shorts will be used for a gradual increase in accelerative loading and to ultimately decide on the right moment for return-to-play to prevent re-injury.

The medical and coaching staffs of the KNVB and KNHB already use systems to monitor different types of load and implementation will be naturally.
As the multi-directional movements around the hip in football and hockey are also present in various other (team)sports and activities, the sensor shorts can be easily made applicable in sports, rehabilitation and occupational medicine as well. The concept is convertible to other joints (shoulder, elbow, knee) and made useful in for instance basketball, handball, baseball, tennis and volleyball. The transformation from a high-standard sensor shorts towards an easy-to-use sensor shorts available for larger groups, results in an increase in usability for recreational athletes.

II·a The problem and proposed solution

Problem and Impact: Hamstring and adductor injuries are a serious health problem in soccer and other team sports with increasing medical costs, but also with high impact for players, teams in elite sports where big money is involved. These injuries often occur at the end of training or match-play but for coaches, trainers and medical staff this is difficult to prevent due to the absence of objective measures that identify overload and muscle real-time.
Proposed Solution: Smart sensor shorts will be developed that can monitor the local movements of soccer and field hockey players and, based on biomechanical models, can translate these data into load and muscle stress indicators for individual players. In this way we can optimize training load and reduce hamstring and adductor injuries. This has a large impact on society since the outcomes of this project will not only be useful for elite sportsmen but also for non-elite sportsmen of all ages in various team sports.

II·b In-kind contributions of users

Inmotio (software, app), 0 in-cash / 21.800 € in-kind
<u>End users</u>
KNVB (Soccer), 80.000 € in-cash / 101.200 € in-kind
KNHB (Hockey), 0 in-cash / 40.072 € in-kind

The end users will be involved from the start of the project. The sensor garments will be developed in several iterations and a zeroth version (using off the shelf acceleration sensors and local data storage) will be tested at the start at the KNVB and the KNHB on players during test and training sessions. Most of the tests and measurements during the project will take place at the facilities of the KNVB campus. At this brand new campus (innovation lab) all the necessary equipment is available for observation and validation such as a VICON system, a LPM system etc. Medical staff (football and hockey) and coaches will be involved in most of the experiments. The PhD students will do most of their work at this campus and working space will be available. In this way, a structural interaction is ensured between the PhD students, scientific supervisors, medical staff and coaches.

III Intellectual property

III·a **Contracts**: not applicable
III·b **Patents**: not applicable

Project P7. Breaking the high load - bad coordination multiplier in overhead sports injuries

Project leader: Prof.dr. H.E.J. Veeger (TUD / VU)
Co-applicant(s): Prof.dr. Frans C.T. van der Helm, Prof.dr. G. Jongbloed, Dr. D Bregman (TUD), Dr. E.A.L.M. Verhagen (EMGO+ Institute for Health and Care Research in Amsterdam), Prof.dr. D. Eygendaal (AMC), Dr. B. Visser (HVA).
Requested research positions: 2 PhD (1.0 fte), 1 PDEng (1.0 fte, 2 yrs), NWP (0.8 fte, 18 mths)

Budget:	**Requested from NWO-domain TTW:**	€ 531 130
	Contribution by users:	€ 107 000 (in cash) & € 220 771 (in kind)
Duration of project:		5 years

I Scientific description of the project

We will develop methods and systems to facilitate the identification (and later also modification) of injury risk factors related to load and intersegmental coordination in tennis and baseball. The challenge is to develop (together with P1 and P3) a feedback system that provides information on the (accumulated) load and key coordination parameters, based on power flow models and ligament loading estimates.

I·a Scientific challenge

In both baseball and tennis, throwing and hitting a ball is a fast pre-planned action based on engrained motor patterns that involve the whole body. In these motions *correct relative timing of body part motions* is essential. Despite the current body of knowledge regarding hitting biomechanics on the one hand and injury-prone structures on the other, no useful guidelines regarding the prevention of overload injuries or the ‘correct’ throwing or hitting technique have been developed. The key reasons for this are:

1. the lack of measurement systems that allow for fast and unhindered recording of motion *timing*;
2. the missing link between motion timing and mechanical loading of anatomical structures;
3. the missing link between mechanical loading, intersegmental coordination and injury risk.

As in tennis and baseball performance is highly dependent on (highly repetitive!) fast pre-planned full-body actions that can only marginally be modified during the action itself, pain, injury or weakness somewhere in the kinetic chain can lead to faulty coordination and related injury elsewhere in the chain, usually more distally at the level of the arm or elbow. Proper retraining of ‘correct coordination’ is essential to be able to return to the sport (RTS). While to date the focus in retraining is on identification of strength imbalance and limitations in range of motion, these are likely only secondary factors in the correct coordination. *Correct relative timing, is believed to be the key factor*. This applies especially to the motion of the scapula, as the bridge between trunk motion (the motor) and arm motion (the ‘whip’). Up till now relative timing has had low attention in rehabilitation practice.In this project we will develop (1) a feedback system on motion timing, link this system to a platform for the monitoring of athlete health status and develop an algorithm for the (interactive) quantification of injury risk (accumulated value) and stroke or throw performance (incidental value); (2) an integrated method, requiring online monitoring of progress, for the detailed quantification of relative timing in and after upper extremity injury to improve rehabilitation, modify injury risk, and facilitate the RTS process.

The project goal is to break the high load - bad coordination multiplier in overhead sports injuries, by developing a system for risk identification and modification through new feedback applications based on *motion timing*.

I·b Methods

Approach: This project uses an integrated approach in which the line data collection – algorithm development – practical application forms the central axis. We will collect data from daily training session of the youth selections of KNBSB and KNLTB (2 x 60 players). Using motion sensors integrated in shirts and a sleeve on we will determine the power produced around each joint, as well as working angles and velocities. For the elbow and shoulder we will link these data to detailed musculoskeletal models to analyse in depth the loads on structures at risk (Ulnar collateral ligament in the elbow, capsule in the shoulder, scapular stabilizers in the shoulder). For tennis the instrumented garment will be combined with an instrumented racket that will provide info on racket handling and ball contact. For baseball the sleeve needs to be mounted with fast new-to-develop sensors allowing for the recording of the fast arm action which is yet impossible with existing systems. In combination with athlete data from an Injury Risk app, these data will form the basis of the algorithm development process.

At the same time 'traditional' biomechanical and clinical analysis of collected data will focus on the solution space needed for mathematical modelling and risk prediction. This hybrid approach combines the best of both worlds and renders 'big data' approaches available for relatively small data sets while maximizing statistical power to produce maximal biomechanical and clinical focus.

The sensor systems will be used to provide feedback to players and coaches, on two different levels:
1. direct recording results on *timing of motion*, calculated as power flow in the form of an auditive or visual single signal; 2.summed recording results on injury risk, estimated from the algorithms developed and based on the summation of the effect of sequential strokes or throws, weighted by athlete status / history and 'correctness' of technique. This will be a indicated as a percentage-at-risk value (0 – 100%).

For the provision of feedback in case of injury or rehabilitation, we will focus on forearm and scapular muscles and combine the system with EMG-recording systems. These will be used to retrain the timing pattern during rehab and in the process of Return To Sport. Feedback will be visual (slow but precise and detailed) in the first stage and auditive (fast, but less informative) in the RTS training process.

Overall we will maximize the combination of technical, mathematical and biomechanical knowhow to create feedback systems that are sufficiently easy and precise as well as unobtrusive for the application in sports conditions. This will lift sports biomechanics analysis to a new level.

State of the art starting points: To extend data with athlete info, we will make use of the OptiForm health monitoring system developed by VUmc, also deployed in P5. This system allows for valid and reliable prospective registration of sports related health problems through a translated and adapted Dutch version of the OSTRC Questionnaire on Health Problems. The model has been developed and evaluated in the tennis and runningHealthyMiles and HealthyTrails studies.

The inclusion of Plux, ManualFysion and MOTEK forcelink as partners in the program guarantees high-level input on the level of bio-electrical signal processing, rehab and training interfaces and shoulder injury diagnostics. Based on past performance, both KNLTB and KNBSB will be able to mobilize their selection players and coaches to be involved in this project and act as subjects and field experts.

I·b Time plan and division of tasks

In WP1.1 (NWP) we will develop high-end arm sensors in an instrumented sleeve for the tennis serve and pitching. Also, data systems will be synchronized with existing emg-feedback system. In WP1.1b, sensor data and algorithms will be integrated in a feedback system to be used for dissemination.

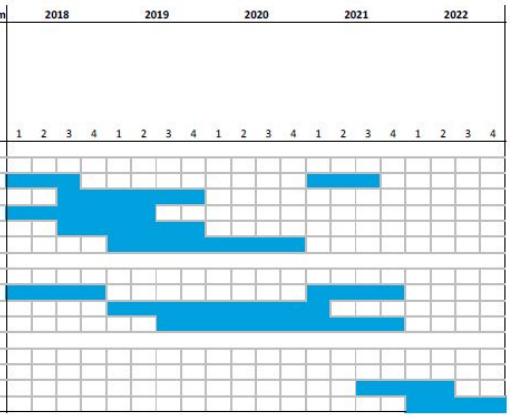
WP1.2 (PhD) comprises collection of data to directly feed the algorithm development, to provide biomechanical data for identification of risk factors. The biomechanical analysis, injury model development and norm technique definition (WP1.2b and 1.2c) will be the task of a PDEng, positioned at MOTEK Forcelink, using their Human Body Model applications.

As last step in the project and part of the WP3 package, the effect of feedback will be evaluated, in close conjunction with both KNLTB and KNBSB and in line with project P3.

Central to the project, and based on sensor data (starting off with the basic version) WP1.3 will focus on the development of algorithms for risk estimates. This project will run in parallel with activities in P4 and P2, in which a PhD position is defined.

In WP2, focusing on Return To Sport, we will extend the sensor system with muscle activity registration, focusing on (superficial) scapular and forearm muscles (WP2.1a), relevant for baseball and tennis. With the extended systems both norm data and patient data will be collected (WP2.2a) during play (norm, patient post injury) and PT diagnostic tests (norm + patient), which will serve as input for timing diagnostics analysis. The results of this analysis (RTS–weighted risk estimates and a Rehab protocol) will be implemented in the feedback system developed in WP1.1b and in a modified feedback system allowing for rehab@home and graded return to sport (WP2.1b). With these instruments and effectiveness analysis will be performed which is indispensable for dissemination of the feedback systems to the paramedical / clinical field (WP3.3).

	TU Delft, BME	VU Amsterdam	EMGO+	AMC	TUDelft, EWI	Motekforce Link	KNLTB	KNBSB	ManualFysion	Plux	Link to program
WP1 Feedback for Prevention											
1.1 (NWP) Sensor and Feedback system development	x	x				x				x	P1, P4
1.2A (PhD1) data collection	x	x	x				x	x		✓	
1.2B (PDeng) Biomechanical analysis											
1.2C (Pdeng) Injury model development						x					
1.3 (PD) Change point analysis	x				x					x	P2
WP2 Return to Sport											
2.1 (NWP) sensor + EMG system development	x	x				x				x	P1
2.2A (PhD2) data collection	x	x		x			x	x	x		
2.2B (PhD2 + PD) Timing Diagnostics Analysis		x					x	x	x		P2
WP3 Dissemination											
3.1 Quick wins (HVA)											
3.2 (PhD1) implementation FB: effect of feedback							x	x			P3
3.3 (PhD2) Effectiveness analysis in PT and clinical practice				x			x	x	x	x	



II Utilisation

II·a The problem and proposed solution

Problem and Impact: For overhead sports there is a demand for specific information on load and timing of explosive motions, linked to long term and incremental injury risk, as well as specific methods for retraining of timing after injury to be able to safely return to sport. This applies especially for the shoulder.

Proposed Solution: A feedback system integrated with a personal status app that will give information on technique, load and accumulated injury risk, based on biomechanical modelling (Motekforce Link)., extended with muscle activity recordings (Plux) for rehab and high-end users. These systems will be used in training (KNBSB and KNLB) and in rehabilitation practice (ManualFysion).

II·b In-kind contributions of users

Motekforce Link is willing to apply a real-time musculoskeletal model, to be personalized to each participant (WP1.2b). Motekforce Link connect it near real-time to motion sensors and EMG recordings..

KNLTB is willing to use the feedback systems for their youth talent groups and apply these to collect sufficient data for WP1.3 and later in the project for dissemination of results (WP3).

KNBSB is willing to use the feedback systems for their youth talent groups and apply these to collect sufficient data for WP1.3 and later in the project for dissemination of results (WP3).

Plux is a young Portuguese company specialised in bioelectrical signal processing. Plux is willing to invest in the application of their Physioplux product to new methods for providing feedback for coordinative timing in sports and in rehabilitation.

ManualFysion, a large physiotherapy company specialized in sports and shoulder rehabilitation, is prepared to assist in rehab training and assessment (WP2) and provide treatment support.

III Intellectual property

To date, there are no patents, transfer agreements or contracts related to the sensor feedback system. Feedback systems for rackets, or for sleeves do exist, but not in combination and to our knowledge not up to the required speed levels.

III·a Contracts: No relevant contracts.

III·b Patents: No relevant patents.

Project P8. Monitor and prevent thermal injuries in endurance and Paralympic sports

Project leader: Prof. Dr. H.A.M. Daanen (VU)
Co-applicant(s): Prof. Dr. T.W.J. Janssen (VU) , Prof. Dr. K.M.B. Jansen, Dr. J.C. van Gemert (TUD), Prof. Dr. M.T.E. Hopman, Dr. T.M.H. Eijsvogels (RUMC), Dr. M. Moen (NOC*NSF), Dr. M.J. Hofmijster (HVA,VU)
Requested research positions: 1 PhD (1.0 fte), 1 PhD (0.5 fte with P1), 1 Postdoc (1.0 fte, 2 yrs), NWP (1.0 fte, 2 yrs)

Budget:	**Requested from NWO-domain TTW:**	€ 421 075
	Contribution by users:	€ 80 000 (in cash) & € 240 560 (in kind)
Duration of project:		5 years

I Scientific description of the project

The challenge for amateurs and professionals who participate in endurance sports and for individuals with spinal cord injuries (SCI) is to maintain thermal equilibrium during a sports event. Thermal injuries (hypo- or hyperthermia) may occur if the balance cannot be maintained. In the heat, the main challenge is to prevent hyperthermia. High body core temperatures reduce the gross efficiency of athletes (about 1% decrease for every 1°C increase in body core temperature (Daanen, van Es, & de Graaf, 2006)) and therefore athletic performance is negatively affected. Paralympic athletes with SCI, especially those with high-level injuries (tetraplegia), not only face the regular thermal challenges as described above, but have a reduced afferent input to their thermoregulatory center, a loss of shivering and sweating capacity and vasomotor control below the level of the lesion. As blood redistribution and sweating are two major thermoregulatory effectors, athletes with SCI are at a considerable risk of heat injury during exercise in thermo-neutral and warm/hot/humid conditions (Boot, Binkhorst, & Hopman, 2006; Veltmeijer, Pluim, Thijssen, Hopman, & Eijsvogels, 2014).

I·a Scientific challenges

- Investigating preparation tools for optimal endurance performance in heat and cold.
- Constructing a cooling system that minimizes thermogenesis and vasoconstriction, so that cooling is optimal for endurance athletes and athletes with SCI;
- Determining the heat sensitivity of individuals and identify cases of heat intolerance;
- Investigating video sensing for assessment of (thermal) fatigue.

The project goal is to improve thermoregulation during sports and assess who is at risk.

I·b Methods

Approach: One PhD student focusses on thermal strain reduction and a shared PhD student with P1 on video sensing for fatigue assessment. The postdoc will apply the knowledge and work on personal cooling systems and protocols for heat strain monitoring and reduction.
State-of-the art starting points: *Thermal strain reduction (PhD1).* Current heat acclimation protocols are stand alone and hardly take the decay into account that occurs during the tapering period prior to the sports event, with a few exceptions (Daanen, Jonkman, Layden, Linnane, & Weller, 2011). We will increase the human potential to deal with extreme heat through the development and evaluation of **novel individualized heat acclimation protocols**. There is increasing evidence that the risk for heatstroke during endurance events in the heat has a genetic background (Hosokawa et al., 2017) and may be assessed using heat tolerance testing i.e. determination of extreme cases in heat sensitivity. The current tests, used in the military (Moran, Erlich, & Epstein, 2007) or for work in protective clothing (Kenney, Lewis, Anderson, & Kamon, 1986) are time-consuming and not applicable for sports. We will **investigate the range of heat sensitivity** in individuals and to design and evaluate

a heat intolerance test for sports application in the lab and in the field (Nijmeegse Vierdaagse). Smart sensor garments will be used for the tests and when heat intolerance is established, smart cooling garments may provide solutions. For cooling, personal systems effectively reduce body temperatures and increase performance (e.g. Bongers, Thijssen, Veltmeijer, Hopman, & Eijsvogels, 2015), however, most systems are cumbersome and intermittent cooling systems (Davey, Barwood, & Tipton, 2013) may provide more effective and energy efficient cooling techniques. We will **investigate validity and usability of personal cooling systems** in a controlled climate chamber as well as during an actual indoors sports event for athletes without and with SCI. In addition we will **evaluate new cooling technologies**, such as ventilation vests effectively used in military settings (Reffeltrath, 2006) or Vortex systems used in work settings. The evaluation will be done in the lab and in the field (e.g., during sailing and cycling meeting the official rules).

Assessment of fatigue using video sensing (0.5 PhD2). Computer vision methods can automatically recognize human emotions such as happy, fear, sad, disgust, and surprise [Khan (2017)] from video. Exciting new work can even estimates clinical depression from facial expressions [Dibeklioglu (2017)]. Here, we investigate the **link between facial expressions and thermally related fatigue**. Next to expressions, fatigue will manifest itself also in motor control which can be extraced from video as dynamics [Zhang (2017)], pose [Toshev (2014)], and behaviour [Yu (2017), Wang (2016)]. We will research video sensing for **linking gross motor control to thermally related fatigue**. All methods will first be validated with the controlled climate chamber and then in actual sport events using the newest MyTemp temperature sensors in the gastro-intestinal system.

I·c Time plan and division of tasks

Work package (WP) 1 will focus on the PhD studies in which new knowledge will be generated regarding maintenance of the thermal balance in heat and cold. In WP2 cooling systems will be adapted by IZI Cooling and evaluated in real-time situations (cycling team Sunweb, Sailing in hot conditions, Nijmeegse Vierdaagse, Watersportverbond) using the MyTemp system. In WP3 the focus will be on dissemination of the acquired information (publications, symposium).

	Members Involved													Link to program	2018	2019	2020	2021	2022
	VU	HvA	TU-Delft	Radboud	NOC*NSF	Hofmijster	Sunweb	IZY body cooling	Sailing Innovation Center	Zevenheuvelenloop/Vierdaagse	Watersportverbond	MyTemp	Reade		1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
WP1 Technology development																			
1.1 PhD thermal strain	x	x		x	x	x	x	x	x	x	x	x	x	P1, P3					
1.2 PhD camera monitoring		x		x		x	x							P1					
1.3 PD technical development	x		x			x		x	x			x	x	P1, P2, P3					
WP2 Technical and experimental validation																			
2.1 Temperature sensors	x							x				x	x	P1					
2.2 Cooling systems	x		x	x				x	x	x	x	x	x	P3					
2.3 Camera system				x			x			x				P1					
WP3 Dissemination																			
3.1 Quick wins (applied universities)		x																	
3.2 Application with sport partners	x						x		x	x	x								
3.3 Application with medical partners		x			x								x						

II Utilisation

The applicants have a good track record in thermal control, technical development ánd application of techniques but most of the work is not yet dedicated to sports. Applications in sport products can be achieved from 2021 onwards, using the expertise applied in other markets like the military. Insights obtained in projects with persons with SCI may be translated to other disorders, like multiple sclerosis, anhidrosis and poikilothermia. The participating companies will utilize the foreground knowledge to improve their products, in particular cooling systems (intermittent individualized cooling). General dissemination plans will be activated in the year 2020 (Olympics/Paralympics Tokyo) and continue in 2021 and 2022.

II·a The problem and proposed solution

The project aims at monitoring and improving thermal control of individuals having difficulties with their thermoregulation, such as 1) healthy individuals engaged in endurance exercise in hot and humid environments or 2) athletes performing exercise in environments with rapidly changing temperatures like the Tour de France, and 3) Paralympic athletes suffering from spinal cord injuries (SCI). To this end, sensors and active cooling devices (thermoelectric coolers, water perfusion pads and forced ventilation) will be integrated in sports garments to allow performance enhancement and preservation of health. The potential of video sensing to detect (thermally related) fatigue will be investigated including gross motor control and facial expression analysis.

II·b In-kind contributions of users

Team Sunweb (20k cash/30k in kind), Watersportverbond (0k/20k), Sailing Innovation Center (0k/20k), Stichting Zevenheuvelenloop (0k/0k) and Nijmeegse Vierdaagse (0k/0k) will provide the field labs and participants for the experiments. The contribution of Reade Rehabilitation (40k/40k) is specifically aimed at the athletes with SCI. They offer a lab for evaluation in the rehabilitation center. MyTemp (0k/20k) and IZI Body Cooling (15k/40k) offer their innovative measurements systems and cooling garments as a starting point for adaptations for the individual athlete.

III Intellectual property

Background knowledge will be specified prior to the start of the project for each partner, so that foreground knowledge can be unambiguously specified as intellectual property.

III·a Contracts

Not applicable.

III·b Patents

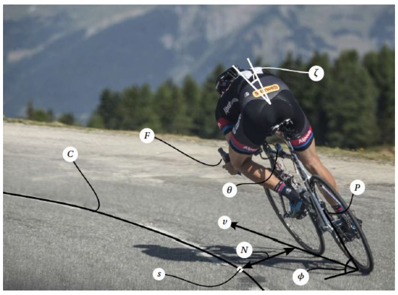
We will explore old and new patents on techniques in cooling systems with the industrial users and NWO.

Project P9. Fall prevention in elite and consumer cycling

Project leader: Dr. ir A.L. Schwab (TUD)
Co-applicant(s): Dr. ir. S. Lukosch, Dr. D. Bregman (TUD, Dr. R.B.Huitema (UMCG), W.J. de Kruijf (NHTV)
Requested research positions: 1 PhD (1.0 fte), 1 PhD (0,5 fte with P3), 1 PostDoc (1.0 fte, 3 yrs)
Budget: **Requested from NWO-domain TTW:** € 459 526
Contribution by users: € 120 000 (in cash) & € 207 992 (in kind)
Duration of project: 5 years

I Scientific description of the project

A bicycle is a laterally unstable system that will eventually fall over without rider control. In recent years, we have gained substantial knowledge about the dynamics and stability of the bicycle itself [1,2]. However, it is the interaction between the rider and the bicycle that will eventually make a cyclist stay upright or not [3]. In this research project, we will focus on two extremes where the interaction between the bicycle and rider may result in decreased stability, and hence falls. Firstly, we will focus on the elderly where speed is low, and the ability to control the bicycle may be reduced. We will specially focus on low speeds, since instability increases with decreasing forward speed. Secondly, we will focus on descent in elite road cycling, where speeds are extremely high, and riders are seeking for the boundaries of the stability of the bicycle. Based on development of generic models and measurements of rider bicycle interaction in both groups, we will develop A) a system to support consumer market cyclist by means of an active lateral stability control system, the so-called steer-assist, and B) feedback mechanisms for fast and safe steering and braking during descents.



I·a Scientific challenge

The first scientific challenge is to integrate sensor technology and develop algorithms for detecting loss of balance in a bicycle. The next challenge, for the consumer application, is to design an active lateral balance control system by means of steer-assist, which stabilizes the bicycle and which shows acceptable behavior to the rider. Not only is there little known on rider control of a bicycle, the concept of shared control is totally novel in single-track vehicles. For the elite sport application computer models need to be developed that can predict optimal steering and braking behavior for fast and safe descent. Further, real-time feedback needs to be provided that assist the cyclist in a fast and safe descent without distracting or confusing the athlete.

The project goal is to detect loss of balance in cycling and prevent falls by either active stabilization by steer-assist and by giving real-time feedback on optimal steering and braking behavior during fast descents.

I·b Method

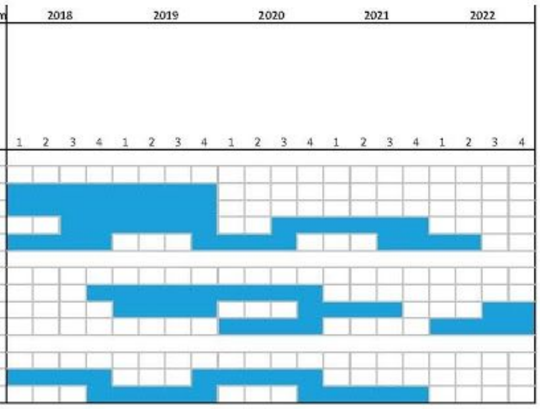
Approach: We will use both model simulations of the bicycle-rider interaction and actual measurements in the field in order to find the algorithms that describe the dynamics of the bicycle, the rider, and their interaction. To get actual information on the state of the bicycle and the rider, a special sensor bike system will be developed, which can be used in both consumer and elite cycling. All sensor signals will be integrated to give a continuous state estimation of rider and bicycle. These state estimations will then be used to develop and optimize the interaction between the rider and bicycle for the situation where an active steer torque (motor) can interfere with the steering behavior, and for elite cycling, by giving the most relevant and useful feedback that may alter the behavior of the rider best.

For the latter, augmented reality feedback mechanisms will be developed and validated that display the most relevant parameters (e.g., ideal descent line, max speed, or break moments).

State of the art starting points: The development of the steer assist for active lateral stability control in cycling builds on more than 10 years of expertise at the TU Delft bicycle lab [1,2,3]. Models for bicycle dynamics and rider control have been developed, based on first principles and experimental validations. Within the current consortium, prototypes of the steer-assist system and the sensor bicycle for measuring elite cycling behaviour during descent have been built by MSc students as proof of principle.

I·b Time plan and division of tasks

	Members Involved								Link to program
	TU Delft - Bicycle lab	TU Delft - Multi Actor S…	UMCG Neuropsycholog…	NHTV Breda	Royal Gacelle	Bosch	Team Sunweb	SWOV	
WP1 Technology development									
1.1 Biclyle state state estimation and steer assist algoritmh (PD)	x					x			P2
1.2 Development bicicye-rider interaction model (Phd1)	x								
1.3 Developments augemented reality environment (PhD2)		x							P3
1.4 Building and intergrating steer-assist proptotype (PD,PhD1)	x				x	x			
WP2 Technical and experimental validation									
2.1 Validating fall detection algorithm (PD)	x		x		x	x		x	
2.2 User interaction and acceptance testing (PhD1)	x		x	x	x	x			
2.3 Augmented reality testing (PhD2)	x	x					x		P3
WP3 Dissemination									
3.1 Quick wins : assessing rider control	x		x	x				x	
3.2 Application with sport partners (cornering feedback)								x	P3



II Utilisation

II·a The problem and proposed solution

In consumer cycling: In consumer cycling, the number of seriously injured cyclist has increased with 30% between 2000 and 2010. Among them 80% are elderly (55+) and 75% are single vehicle accidents [4]. Clearly the instability of the vehicle plays a role here. The societal costs per seriously injured persons are high (around 280 k€ per case) and a cost reduction of approximately 9 million € per 1% reduction in seriously injured cyclists is expected. We therefore aim to develop a so-called steer-assist system. This system enhances the lateral stability of the bicycle by means of active control by a motor that is integrated in the steering column. Such is a system is very apt for electrically assisted bicycles, which is a growing market among the elderly. In close cooperation with Royal Gazelle and Bosch we aim to introduce such system into society during or shortly after the project has finished.

In elite cycling: In road (elite) cycling, falls resulting in serious injuries are problems with high medical costs. Moreover, the way in which an elite cyclist steers and controls the bicycle during descent in a race can make the difference between winning and losing. We will develop and validate models that predict optimal steering and braking behavior as well as augmented reality feedback mechanisms indicating optimal steering and braking behavior. We expect this to result in a reduction of falls as well as faster and safer descents. This will give the Giant Sunweb cycling team a competitive advantage and will eventually lead to a safer sports environment.

II·b In-kind contributions of users

Royal Gazelle will provide the integration of the developed steer-assist system and sensors onto their bicycles. Moreover, Gazelle will provide access to their Experience Centres, where new prototypes can be tested with riders. Bosch provides the integration of the sensor technology and steer-assist systems with their e-bike modules. Team Giant Sunweb will provide support of their embedded scientist for data interpretation, will facilitate field tests, and provide bicycles and elite cyclists. The SWOV will cover rider acceptance and human factors.

III Intellectual property

III·a Contracts

There are no contracts that may obstruct the utilization of the research results.

III·b Patents

Bosch holds the following patents that are relevant for the project. The patents do not obstruct the utilization of the knowledge developed in the project.
DE 10 2017 202938 A1 (23.02.2017): Lenkwinkelgeschwindigkeitsabhängiger passiver Lenkungsdämpfer
DE 10 2016 225497 A1 (PT 19.12.2006): Lenkunterstützung für Fahrradfahrer in Unfallsituationen
DE 10 2016 216563 A1 (PT 01.09.2016): Automatisierter variabler Vorbau am eBike
DE 10 2013 214517 A1 (PT 25.07.2013): Aktive Lenk- und Stabilisierungsvorrichtung für Pedelecs: Elektro-Maschine mit Ansteuerung und Getriebe für Stabilisation, Sicherheit und taktiles Feedback
Internal documented ideas in preparation for patent application:
2017/2909 (2017/3133; 2017/3127), 2017/1541, 2016/4887, 2016/4792, 2016/4647

9. Appendices

9.1. Abbreviations and acronyms

AMC	Academic Medical Center Amsterdam
CAS	Citius, Altius, Sanius (*Faster, Higher, Healthier*)
ECSS	European College of Sport Science
EMG	Electromyography
Fontys	Fontys University of Applied Sciences
HAN	HAN University of Applied Sciences
HvA	Amsterdam University of Applied Sciences
HH	The Hague University of Applied Sciences
HMD	Head-Mounted Display
ISEA	International Sports Engineering Association
ITF	International Tennis Federation
KCSportNL	Knowledge Centre for Sport Netherlands
KNBSB	Royal Netherlands Baseball and Softball Federation
KNHB	Royal Dutch Hockey Federation
KNLTB	Royal Dutch Lawn Tennis Federation
KNVB	Royal Dutch Soccer Federation
LEI	Leiden University
LPM	Local Position Measurement
LUMC	Leiden University Medical Center
NCPs	National Coach Platforms of NOC*NSF
NHTV	Breda University of Applied Sciences
NOC*NSF	Dutch National Olympic Committee
RUG	University of Groningen
SCI	Spinal cord injury
SWOV	Dutch Institute for Road Safety Research
TUD (TU Delft)	Delft University of Technology
TUE (TU/e)	Eindhoven University of Technology
UMCG	University Medical Centre Groningen
VU	Vrije Universiteit Amsterdam
VUMC (VUmc)	VU University Medical Center

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