A FIBRE-OPTICAL SENSING APPROACH

Although running-specific prostheses (RSPs) already allow amputee sprinters to run almost as fast as able-bodied sprinters, new ways of measuring these prostheses are still being developed to help amputee sprinters run even faster. In the project described in this article, a measurement system for RSPs was developed that is able to measure the ground reaction forces (GRFs) while sprinting. It uses Fiber Bragg Grating sensors to measure the strain in the prosthesis, from which the GRFs can be calculated. The measurement system was shown to hold up under the wear and tear of a sprinter's environment, while also recording valuable data for athletes.

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Introduction

Running-specific prostheses (RSPs), made of carbon-fibre composite material, already allow elite transtibial amputee sprinters to perform comparably to the best able-bodied sprinters in the world. In the 100-meter track sprint for the T62 (double below-the-knee amputation) and T64 (single below-the-knee amputation) classes, the world records at the time of writing were 10.54 seconds by Johannes Floors and 10.61 seconds by Richard Browne, respectively. When compared to the record 9.54 seconds by an able-bodied athlete, in this case Usain Bolt, it can be seen that these times are fairly close.

When looking into the sprinting dynamics of amputee athletes, the difference between able-bodied sprinters and amputee sprinters can be found at the start of the sprint, the so-called drive phase, where the athlete accelerates to top speed. Among other factors, previous studies found that the limited ability of amputee athletes to exert high forward forces onto the track (so-called ground reaction forces, or GRFs) is one of the most important causes of this low acceleration [1] [2]. Also, coaches of several paralympic training groups could confirm that this GRF generation at the start of a sprint is a factor that is heavily focused on during training.

Part of this limited GRF generation can be explained by the lower muscle mass of amputees in their lower leg(s). However, a second cause could be that the prosthesis does not allow them to accelerate faster.

Prosthetics design

Although RSPs appear to have a relatively simple design, the combination of human-prosthesis interaction, the prosthesis' non-intuitive dynamic behaviour and its material properties make for complex design parameters. At first glance, the prosthesis can be considered a linear spring; it stores energy at initial ground contact, which is then released very efficiently at toe-off. However, the geometry of the prosthesis also converts the vertical spring force into a forward propelling force. This not only makes the design of the prosthesis itself more complex, it means the validation of the design also needs to be extensive.

Initially, the goal in this project was to design a prosthesis that would allow amputee sprinters to attain a higher propelling force and thus a higher acceleration. In order to develop a prosthesis design that enables amputee sprinters to run even faster, highly detailed information about the prosthesis behaviour during sprinting is needed, specifically about GRFs.

An analysis of the currently used GRF measurement methods revealed that a measurement system that allows for repeatable measurements throughout an entire sprint, which is also suitable for the sprinting environment, is not readily available. Therefore, the scope of the project was changed to the creation of this GRF measurement system; specifically, the design of an instrumented prosthesis that allows for GRF measurements throughout an entire sprint.

Fibre-optical sensing

Other instrumented prosthetics that measure forces have already been developed in other studies, but these instrumented prosthetics have their limitations both in the rough training environment in which they are used and in practical applications. Petrone *et al.* used a strain gauge sensor system that was attached to the surface of the RSP [3]. Although the results of this sensor system were adequate for the intended application, the system is rather bulky and, as it is attached to the outside

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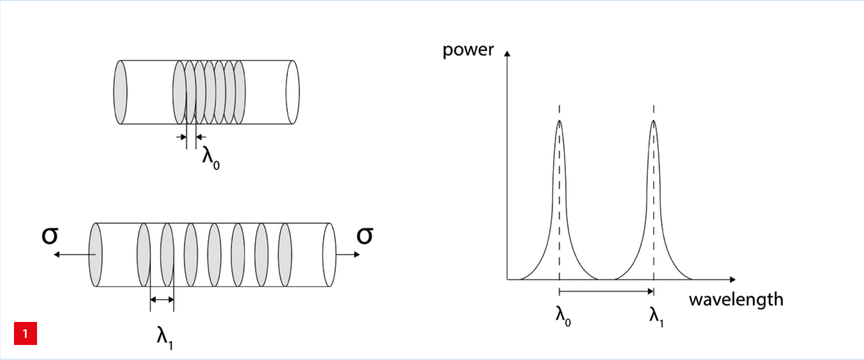


Working principle of FBGs; see the text for further explanation.

of the prosthesis, is also more prone to breaking in the rough sprinting environment.

Galvão *et al.* took a fibre-optical sensing approach (FOS) [4], which uses the transmission and detection of light signals. Fibre Bragg Gratings (FBGs) (Figure 1) are an example of a FOS application, where a Bragg reflector is used as an intrinsic sensor. The gratings used in these sensors are inscriptions in an optical fibre that work according to the Fresnel reflection principle: a small portion of the light is reflected, and the other portion is refracted at the interface of the inscriptions. This way, the portion of the light that has been reflected with principal wavelength λ_0 is sent to a detector (called an interrogator), while the other portion of the light propagates through the fibre.

When the fibre at the location of the FBG elongates, the grating period changes and hence the observed wavelength (λ_B) of the reflected light will be different. Therefore, by monitoring the reflected spectrum, the strain in the FBG sensors can be measured. As the sensor only reflects a part of the light emitted by the light source, it is possible to place multiple sensors in series in one fibre. Then a reflected spectrum with multiple peaks of different principal wavelengths, each determined by the sensor's grating period, will be observed. In this case, it is important that no interference between the reflected spectra occurs, since the sensor reading will then be flawed.

In Galvao's system, 17 embedded FBG sensors were used, which were calibrated by directly correlating the measured strains in the sensors to the applied forces on the RSP. Although these results were also adequate for the application, the high number of sensors needed for this solution meant that it was fairly expensive to manufacture. Additionally, this system comprised two optical channels, meaning that two separate fibres with embedded sensors were used. This has its restrictions when making the sensor system mobile for use in training, as mobile interrogators that use more than one channel are not readily available.

Requirements

Due to the practical limitations of these sensor systems, a more application-oriented approach was taken by creating an instrumented prosthesis with a simpler set-up that could eventually be embedded in the prosthesis itself.

The measurement requirements for this project were as follows:

- The system should be able to detect the horizontal and vertical GRF components.
- The system should be able to detect the point of GRF application.
- The sensor system should have a measurement error (variance and bias) of lower than 5% of the maximum GRF in x- and y-direction.
- The sampling rate of the system should be at least 1 kHz, to account for adequate data-analysis possibilities given that contact times of 0.2 s are expected.
- The application of the sensor system should not alter the mechanical characteristics of the RSP.

The practical requirements for this sensor system were:

- The weight of the measurement system added to the RSP should not exceed 0.100 kg.
- The sensor system should not impair the gait of the athlete.
- The external device size of the sensor system should not exceed 200 mm x 300 mm x 300 mm.

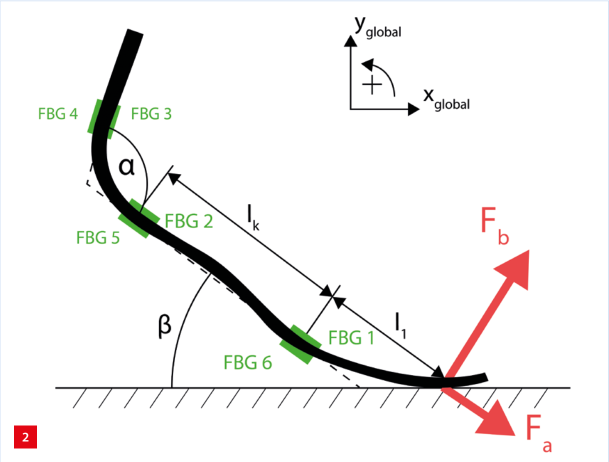
Why FBGs?

In general, the composite material in RSPs is laid up layer by layer manually, thus allowing for the embedding of sensors within the material. For this application, FBG sensors were used: strain sensors written into a glass fibre of approximately 125 μm in diameter. These sensors and their read-out devices allow for the required high sampling frequency and are capable of measuring at a high-enough resolution with the accuracy required for this application. Also, the expected strains of the prosthesis could be handled by these sensors.

Sensor design

For the application design of the instrumented prosthesis, the integrated photonics company PhotonFirst was approached. This company has a wealth of experience in the application design of FBG sensor systems, so it was able to help select the appropriate sensors as well as develop the sensor layout and the spectral design, and manufacture the instrumented prosthesis.

For this project, use was made of Femtosecond FBG sensors from FBGS. In total, three FBG sensor bridges were placed on the surface of the prosthesis: each time, one sensor on top and one on the bottom (Figure 2). From their signals



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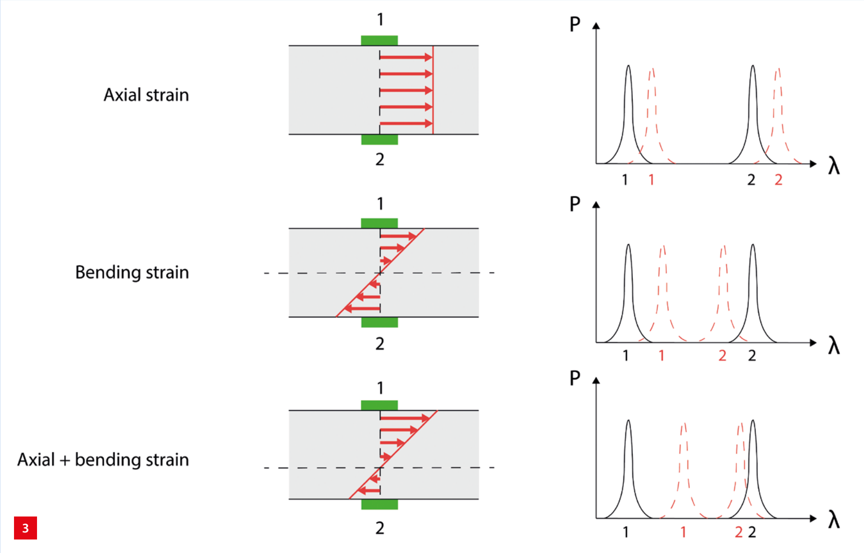
Schematic drawing of FBG placement on the prosthesis. Using the axial and bending strain components measured in the FBGs, F_a and F_b, the GRF components at the point of application in the RSP reference frame, can be calculated. Also, the location of the point of application, defined by l_1, can be determined from the calculations.

the internal axial and bending strains, and therefore the internal forces of the material, were calculated. These internal forces were used to determine the GRFs using an abstracted model in Matlab (Figure 3).

As the expected strains of the sensors were fairly high, in the range of 3,000 με (microstrain), the spacing (the wavelength differences between the various sensors) in the spectral design had to incorporate the possible strains as well. The initial deformation of the prosthesis would mean that the sensors at the top would experience a negative strain and the sensors at the bottom of the prosthesis would experience a positive strain. After toe-off, however, the sensors would indicate an inverse strain. It was therefore necessary that the spacing in the wavelength domain was sufficiently adequate so that no interference of FBG wavelengths would occur.



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Expected strains in FBG strain bridges. In the case of an axial strain, both the top and bottom sensors will return a higher wavelength value than in an unperturbed system. In the case of a bending strain, the top FBG will return a higher wavelength value, while the bottom sensor will return a lower wavelength value. During testing, it was expected that a combination of both strain types would occur.

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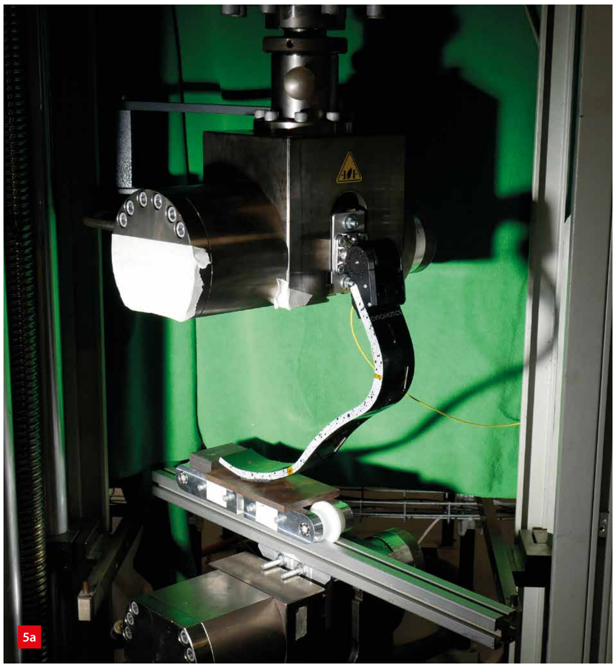
ArcX Extreme prototype instrumented with FBG sensors.

Prototyping

For the first proof of concept, the sensors were attached to the surface of the material. This prototype was constructed using an existing Ottobock 1E90 prosthesis. At PhotonFirst, the sensors were glued to the composite material and the sensor fibres were connected by means of an FC-APC (Ferrule Connector – Angled Physical Contact) connector in series, so that only one channel on the interrogator could be used. After constructing the prototype, noise levels in the system were determined, which were shown to be relatively low considering the amount of strain that was expected.

For a second prototype, Gyromotics, a prosthetics company that specialises in daily-life and sports prostheses, was approached and was able to provide a prototype of a sprinting-specific prosthesis for the purpose of field testing with an athlete. This ArcX Extreme prosthesis was instrumented similarly to the first prototype (Figure 4); however, fragility and weight in this prototype were reduced by cutting the fibres to the appropriate length and by splicing the fibres instead of using FC-APC connectors.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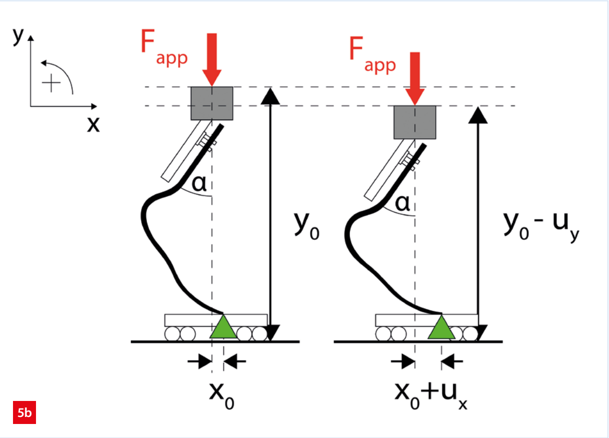
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Calibration set-up in the compression bench with a horizontally rolling platform.
(a) Realisation.
(b) Schematic overview, showing the tip displacement in the x-direction induced by a compression in the y-direction.

Calibration

The prototypes were first calibrated in an experimental set-up in a mechanical compression bench (Figure 5). This set-up consisted of a vertical displacement-controlled actuator and a horizontally rolling platform. The vertical force at the actuator could then be determined via strain sensors in the compression head. The axles of the sliding platform were equipped with bearings in order to minimise friction in the system. The prototypes were tested with a Photon-First GTR interrogator, which allowed for a sampling frequency of 19.28 kHz.

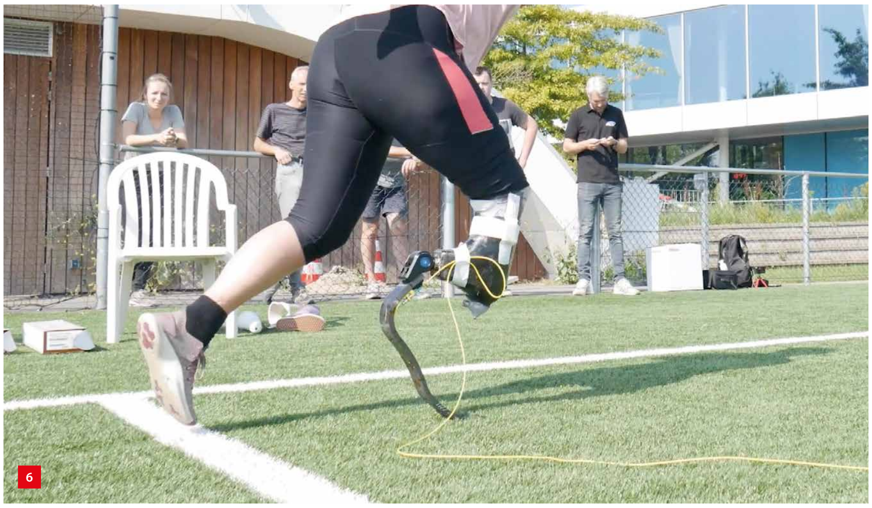
After calibration, this measurement system showed a linearised sensitivity of 0.121 N/με with a resolution of about 0.05 N. A precision of about 22 N was observed during repeated calibration trails. Considering that the expected forces were in the range of five times the body mass of the user (70 kg), these results were adequate for such a sensor system. These compression tests showed that the measurement system complied to the design requirements and that it was possible to estimate the point of application of the GRF. However, since the calibration method could only take into account the forces in the *y*-direction, no calibration of the forces in the *x*-direction could be performed.

Field testing

After calibrating the ArcX Extreme prototype, the sensor system was used in a field test with an athlete at the Team Frank Jol company (Figure 6). The prosthesis was mounted and aligned to a socket that fit the athlete. As an addition to the FBG sensors on the prosthesis, inertial measurement units (IMUs) were mounted onto the socket so that the orientation of the prosthesis with respect to the ground could be obtained during the activities that the athlete had to perform. For the full set-up, see Figure 7.

The protocol consisted of three exercises, each in three variants. First, a weight shift exercise was done in which the athlete had to shift her weight from one leg to the other while in a standing posture. This was done at three different speeds. Then the athlete was asked to walk with the prosthesis in three different stride lengths. Lastly, the athlete was asked to run on the prosthesis, again in three different stride lengths.

In terms of the sensing capabilities, the FBGs displayed a clear response to the perturbations exerted on the RSP. This was shown in the results of the field tests, where the cyclic impulse from the touchdown of the RSP could be observed clearly in the resultant GRF measurements (Figure 8). No FBG interference occurred during the compression or the field testing. In the early movement phase, negative *x*-forces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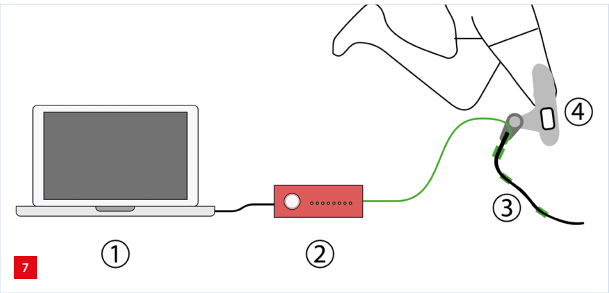
Field testing with an athlete at Team Frank Jol, located at the Friendship Sports Centre in Amsterdam (NL).



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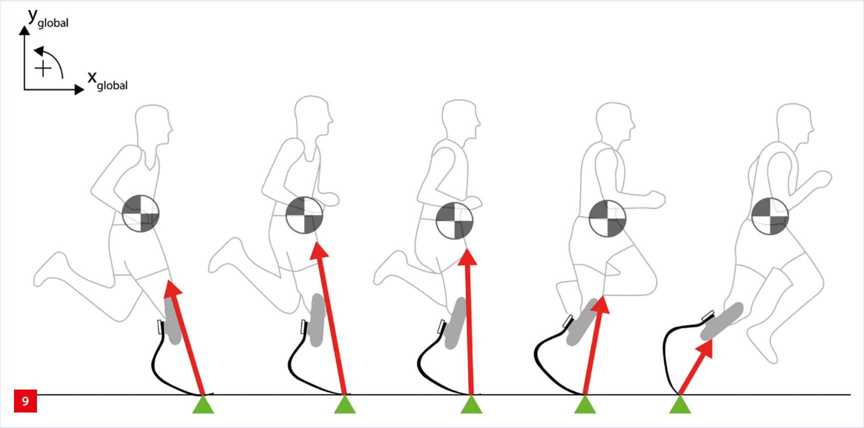
Test set-up for the field tests. The laptop (1) is connected to the FBG interrogator (2) (PhotonFirst GTR). The instrumented Gyromotics ArcX Extreme prosthesis (3) is connected to the interrogator via a patch cable. The IMU (4) (Shimmer 3, wireless) is used to record the orientation of the stump relative to the global reference frame.



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During the contact phase, the x-component of the ground reaction force (red arrow) changes from negative to positive.

are observed, meaning that at initial contact the athlete's centre of gravity is still behind the point of contact (Figure 9). During the contact phase, the centre of gravity moves over the contact point and the negative *x*-force becomes positive.

Conclusion

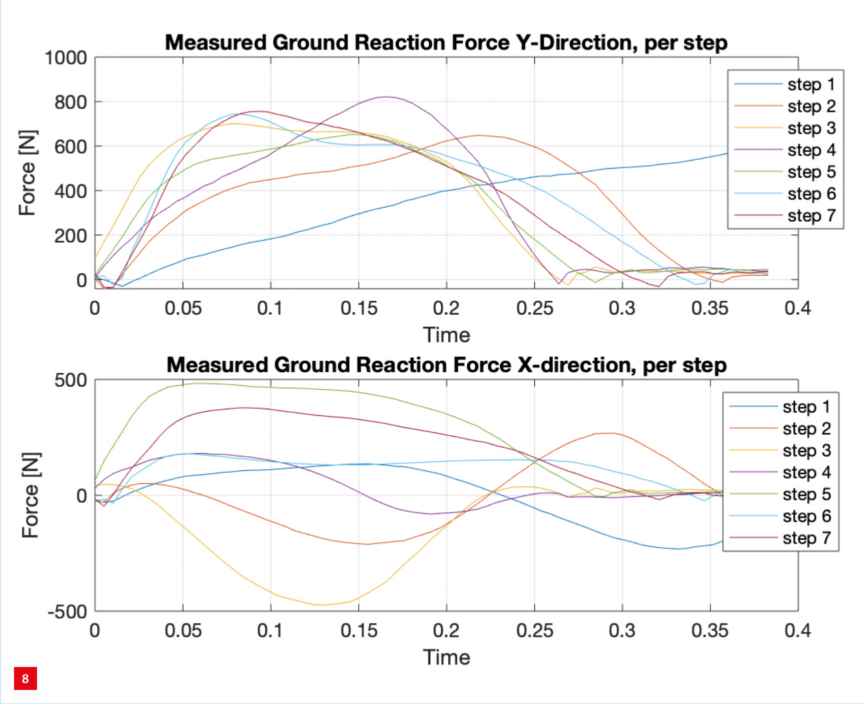
Overall, the sensor system was shown to comply with the measurement and practical requirements that had been set beforehand. The system added no significant weight to the prosthesis, and due to the low amounts of adhesive used, it is unlikely that the mechanical properties of the prosthesis were altered. The repeated calibration trials showed that the measurements were precise and accurate enough for this type of application.

However, the calibration method (based on compression in the *y*-direction) has its limitations in the *x*-direction and thus the forces in that direction could not be obtained reliably. Therefore, a calibration method should be considered that allows for measurements in more than one degree of freedom to validate the method of calculating the forces in the *x*- and *y*-direction. Additional measurements with force plates need to be performed to further validate the findings.

To make this sensor system work in a training environment, the system has to be embedded within the prosthesis. When accompanied by a wireless interrogation device, this could be a set-up that enables prosthesis design to develop further and allow track sprinters to adjust their technique accordingly. This will mean that, eventually, the gap between able-bodied sprinters and amputee sprinters will close.

REFERENCES

[1] Willwacher, S., *et al.*, "Sprint Start Kinetics of Amputee and Non-Amputee Sprinters", *PLOS ONE*, vol. 11 (11), e0166219, 2016, *doi.org/10.1371/journal.pone.0166219*
[2] Grabowski, A.M., *et al.*, "Running-specific prostheses limit ground-force during sprinting", *Biol. Lett.*, vol. 6 (2), pp. 201-204, 2010, *doi.org/10.1098/rsbl.2009.0729*
[3] Petrone, N., *et al.*, "Development of Instrumented Running Prosthetic Feet for the Collection of Track Loads on Elite Athletes", *Sensors*, vol. 20 (20), 5758, 2020, *doi.org/10.3390/s20205758*
[4] Galvão, J.R., *et al.*, "Smart Carbon Fiber Transtibial Prosthesis Based on Embedded Fiber Bragg Gratings", *IEEE Sensors Journal*, vol. 18, pp. 1520-1527, 2018.



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Measured GRF for the regular running trial. The single steps are plotted such that at t = 0 the RSP has initial contact with the ground. The individual lines represent the steps of the trial. In the GRFy profile all but the first step follow a similar impulse pattern, with a similar contact time (i.e. the time during which F does not equal zero). The GRFx profile is less consistent, as more variability is shown between individual steps.