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Corresponding Author: Dr. Philip Riches,

Corresponding Author's Institution: University of Strathclyde

First Author: Heather I Black

Order of Authors: Heather I Black; Sylvie Coupaud; Niamh Nic Daeid; Philip Riches

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This research investigated bruising using a standardised blunt impact, delivered to 18 volunteers. The resulting bruise was imaged using colour, cross polarised (CP) and infrared photography. Timelines of the L*a*b* colour space were determined from both colour and CP images for up to 3 weeks.

Overall, no single photographic technique out-performed the others, however CP did provide greater contrast than colour photography. L*a*b* colour space timelines were not attributable any physiological characteristics. Whilst impact force negatively correlated with BMI (R2=0.321), neither were associated with any measure of bruise appearance.

Due to the inter-subject variability in the bruise response to a controlled infliction, none of the methods in the current study could be used to reliably predict the age of a bruise or the severity of force used in creating a bruise. A more comprehensive approach combining impact characteristics, tissue mechanics, enhanced localised physiological measures and improvements in quantifying bruise appearance is likely to be essential in removing subjectivity from their interpretation.

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Title Page (with authors and addresses)

On the relationships between applied force, photography technique, and the quantification of bruise appearance.

Heather I. Black[a], Sylvie Coupaud[a], Niamh Nic Daéid[b], Philip E. Riches[a]

[a]Department of Biomedical Engineering, University of Strathclyde, Wolfson Centre, 106 Rottenrow, Glasgow G4 0NW

[b]Centre for Anatomy and Human Identification, University of Dundee, Dundee

Address for correspondence:

Dr Philip Riches
Room 874, Graham Hills Building
University of Strathclyde
50 Richmond Street
Glasgow
G1 1XU

T: +44 (0)141 548 5703
E: philip.riches@strath.ac.uk

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***Highlights (for review)**

Highlights FSI-D-19-00584

- Bruise colour timelines were not attributable to physiological characteristics
- Impact force decreased with increasing BMI
- Impact force was not relatable to bruise appearance
- Bruise age, and the impact force used, are not predictable by current methods

Abstract

Bruising is an injury commonly observed within suspect cases of assault or abuse, yet how a blunt impact initiates bruising and influences its severity is not fully understood. Furthermore, the standard method of documenting a bruise with colour photography is known to have limitations which influence the already subjective analysis of a bruise.

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Due to the inter-subject variability in the bruise response to a controlled infliction, none of the methods in the current study could be used to reliably predict the age of a bruise or the severity of force used in creating a bruise. A more comprehensive approach combining impact characteristics, tissue mechanics, enhanced localised physiological measures and improvements in quantifying bruise appearance is likely to be essential in removing subjectivity from their interpretation.

Introduction

Bruising is the most commonly observable injury following physical assault, but there is minimal reliable information which can be ascertained from a bruise's presence with regards to its formation. This is problematic within a legal context as the size and shape of a bruise are subjectively related to bruise age and to the force used to create it. Therefore, it is not uncommon for there to be differences in opinion in the interpretation of the information which a bruise can provide during a court case [1,2].

The manifestation of a bruise is known in terms of blood vessel rupture, repair and blood breakdown [3-5], however many other factors can influence the bruising process including age; adiposity, anatomical location and diet [6-11]. Thus, no two bruises will be exactly the same.

The determination of bruise age is subject to human interpretation [12]. Individuals perceive colours differently [13], particularly the colour yellow, which is considered one of the most important colours in bruising supposedly indicating an older bruise as haemoglobin is broken down to billirubin during the healing process. Numerous studies have attempted to improve visual bruise interpretation and remove subjectivity: including colour charts as a visual aid [14]; utilising specific colour measurement tools [15-18]; and using histology and measuring the chemical components of a bruise via hyperspectral imaging [19,20]. However there has been little success. An earlier study which attempted track colour changes notably found that yellow was unlikely to be seen in bruises younger than 18 hours [21] and this visual analysis time-frame has yet to be made more specific. More invasive approaches have also been considered such as taking bruise biopsies [22]. However, despite the varied approaches, there is yet to be a proven and practical alternative to replace visual analysis.

Colour analysis is further complicated as how a bruise in perceived *in vivo* may be different to its interpretation from an image [12]. Standard colour photography can either add or remove details with exposure. Furthermore, lighting conditions can strongly influence the observed depth of colour. The use of ultraviolet, infrared, cross polarised and alternate light source photography have all been tried, with the aim of addressing these issues [23-27]. However, there is yet to be an accepted and validated photography protocol to replace the standard colour photography currently used.

One important factor rarely considered experimentally is the bruise's mechanical aetiology: the influence of the mechanics of a blunt impact on the appearance and time history of a bruise is unknown. Desmoulin and Anderson [28], did investigate bruise mechanics with one volunteer but their results were inconclusive.

Therefore, the objectives of this research were: (i) to assess and compare the suitability of colour, cross polarised and infrared photography techniques for extracting useful information regarding bruise formation; (ii) to investigate the use of a colour model for monitoring a healing bruise; and (iii) to correlate these findings with a known mechanical aetiology of the bruise, together with physiological measures.

Method

Ethics and Participants

Following fully informed consent, 18 (8 males 10 females) people volunteered (ages 19 to 32). The volunteer pool was predominantly White (15 of 18), with the other three being Arab, Asian or Black. Exclusion criteria included anyone who was taking any anti-coagulant, anti-platelet or anti-inflammatory medication; taking oral or injectable steroids; diagnosed with any medical conditions which affected blood clotting or platelet function; had received an organ transplant or donated blood or blood products; pregnant; and had undergone major surgery or had significant scarring, tattoos or piercings to the thigh. Participants completed a consent form and a general health questionnaire allowing volunteers to be categorised by age, gender, BMI (Body Mass Index) and BSA (Body Surface Area), ethnicity, smoking habits, alcohol consumption, medication/food supplement intake and exercise habits. All aspects of the research were performed following the approval of the university's institutional Ethics Committee.

Bruise Generation

Volunteers wore tight fitting Lycra™ black shorts or leggings and stood with their right, lateral, mid-thigh region positioned behind an 8 cm diameter hole in a protective screen. A paintball marker (BT-4 Combat, Just Paintball, UK), perpendicularly 6 m away, fired a single reusable rubber paintball (1.6 cm diameter, mass 2.6 g) through the hole which impacted the thigh.

Photographic method

Volunteers returned to have their bruise imaged on alternate days post impact for 3 weeks, or until their bruise was no longer distinguishable using any imaging modality. Three perpendicular control images of the lateral right thigh were taken at each session: colour and cross polarised (CP) images using a Nikon D300 DSLR and infrared (IR) images using an IR-converted Nikon D300 DSLR, both fitted with a Nikkor 60 mm lens. For each person, both colour and CP images of an X-Rite ColourChecker™ were also taken for image standardisation. The room (with no windows) was fully lit with artificial neon tube lighting, and the camera flash was used for both colour and CP images and separate IR light source. For CP images, linear polarising filters (Knight Optical, UK), were positioned at 90° to each other over the flash and the lens. Camera settings were an auto ISO and a F-stop of 4.5. Metering mode was "pattern" for colour and IR images, and "spot" for CP images. All images were saved as the raw format (.NEF file), and an ABFO NO.2 bite mark scale was used for reference.

Force determination

A Photron Fastcam SA4 high speed camera (Photron (Europe) Ltd., UK), with a single Photron High Power multi LED lamp (Photron (Europe) Ltd., UK), and fitted with a Sigma 24-70 mm lens (Photron (Europe) Ltd., UK), was positioned and manually focussed to the thigh, to capture the impact. The camera angle for each impact was determined using a 10 x 10 cm scale grid. The paintball trajectory was tracked using custom software (Matlab, Mathworks, U.S.). The camera's frame rate was set at 40 kHz and a 4^{th} order Butterworth, zero-lag, low-pass filter was applied to positional data with a cut-off frequency of 3.5 kHz. Numerical derivatives of the trajectory determined paintball velocity and acceleration. Multiplying paintball horizontal acceleration by its mass determined the impact force with horizontal deceleration of the paintball implying a positive force of the paintball on the thigh.

Image analysis

All images were standardised and analysed using Photoshop™ (Adobe Systems). Colour and CP images were standardised using the X-Rite ColorChecker Passport [29, 30]. As there was no colour reference for the IR images, white balance was set for each image from a white part of the measurement scale. Once standardised the contrast of the IR image was adjusted using the ''curves'' function. Both the original standardised IR image and the altered contrast IR image were saved, thus for each bruise there were 4 images: colour, CP, IR and altered IR.

Bruises typically took on a doughnut appearance, the area of which was determined manually using a lasso tool around the outer and inner extents of the bruise discolouration, by the same observer in every image. In doing so, the area of the impact mark and internal clear zone, were excluded from subsequent analyses. Both colour and contrast measurements were based on the method proposed by Baker et al. (2013) [23]. Briefly, colour and CP images were converted from RGB to L*a*b* and two 1 cm diameter areas were identified within the bruise and three from the surrounding non-bruised skin: preferentially taken proximally to the bruise area and ±120° from this position. The colours in each area were averaged and the difference between the bruised and non-bruised areas determined the L*a*b* profile for each image. Contrast measurements were performed using Photoshop™: all images were converted to greyscale, and the average luminosity taken in the same areas as the colour analysis, with the difference between the two being recorded as the contrast value. The same process was used for the IR and altered IR images.

Statistical Analysis

Bivariate relationships were graphically assessed and Pearson correlation coefficients used to quantify any associations between variables. The effect of photography technique on image variables followed Shapiro-Wilk tests to ascertain data normality, with the appropriate tests (e.g. t-tests (paired or independent), Wilcoxon-Signed Ranks test, Mann-Whitney U-test or repeated measures ANOVA) being subsequently performed. All statistics were performed using SPSS version 24 and and the null hypothesis rejected if $p < 0.05$. Data are presented as mean values ±1 standard deviation.

Results

Bruises

Impact velocity was 69.1 ± 2.78 ms^{-1}. In some cases, the ball was obscured at impact, leading to data from 5 participants being excluded from force analyses. Peak force was 917 ± 141 N. Of all the characteristics considered in the questionnaire, only BMI significantly correlated, negatively, with peak force, albeit moderately ($R^2 = 0.321$, $p = 0.043$, Figure 1).

The majority of bruises presented as a doughnut shape (Figure 2): circular with a central clear zone. For some, the bruise was more of an oblong shape suggesting a non-perpendicular impact trajectory, or had a non-specific shape with no central clear zone. Almost all bruises appeared with a red circular mark located within the central clear zone. This could be considered intradermal bruising, however this could not be confirmed as it was only visible in some or the IR images. Bruise area peaked around day 3 to 7 (Figure 3) with a large variance in bruise size and colour apparent (Figures 2, 3).

There was minimal evidence of any associations between physiological characteristics, impact mechanics and bruise shape and size. Gender significantly affected the impact mark area observed from the IR images ($p < 0.05$), suggesting the immediate damage was larger for females than for males. Lightness (L^*) of the immediately visible impact mark, using both colour and CP techniques also varied with gender ($p = 0.041$ and $p = 0.006$ respectively), implying that the initial injury was darker for females compared to males. However, one male clearly did not conform to this trend, giving uncertainty in dichotomising findings with regard to gender. There was a general trend over the lifetime of the bruises going from dark to light (ΔL^*), green to red (Δa^*) and blue to yellow (Δb^*) (Figure 4), with no association with physiological characteristics evident.

There was no significant difference between photographic techniques on the number of days a bruise was visible ($p = 0.157$), however photographic technique influenced the contrast between bruised and non-bruised skin: with the exception of colour and IR imaging, post-hoc analysis revealed significant differences in peak contrast measures between the remaining photographic techniques ($p < 0.001$ in each case, Figure 5). As the bruise began to fade, contrast reduced (Figure 5). IR photography (both original and altered images), identified peak contrast approximately a day before the colour and CP images. Contrast was not dependent on skin tone, BMI or gender category. Day one ΔL^* values were lower for CP compared to the colour images ($p < 0.001$) and CP photography also significantly increased peak Δb^* ($p < 0.001$).

The maximum bruise area varied greatly between individuals, ranging from 5.49 cm^2 to 41.5 cm^2 across all photographic techniques. Colour and CP impact mark bruise areas differed ($p < 0.001$, Table 1) and the IR and IR (altered) impact mark areas also differed ($p = 0.004$). As the IR images detected immediate bruising not visible to the eye, the impact mark was larger compared to colour and CP methods (both $p < 0.001$, Table 1). The area of the impact mark of the altered IR images was not significantly greater than that of the unaltered IR images. When the bruise appears at its largest, there were no significant differences in maximum areas between the imaging modalities ($p > 0.05$, Table 1).

Discussion

This study used single, controlled, impacts on 18 volunteers and determined the biomechanics of the impact, and the size and shape and colour of the resulting bruise using four different photographic techniques in an attempt to identify relationships between the bruise and basic physiological characteristics. Doughnut shaped bruises were predominantly observed. When this was not the case, we suggest that variance of shape was associated with a variation in the angle of impact, exacerbated by the curvature of each individual thigh. A wide range of colours and sizes were evident, with no immediately obvious link to the cause of variation. During bruise formation and healing, colours developed and faded in a similar timeframe, although the intensity and range of colour tones varied between individuals, not ascribable to individuals' characteristics. The extent of colour variability in our data suggest that visual interpretation of colour is inaccurate: colour was not relatable to bruise age or to the level of force which caused the injury, irrespective of photographic technique.

This study for controlled impact velocity and hence the energy transfer between projectile and tissue. However, the applied force is not only a function of the impact velocity, but also the stiffness of the rubber ball (although this too was a constant) and soft tissue beneath the impact site. Deformation of both reduces the impact force by increasing the impact time and thus decreasing the deceleration of the ball. There was a negative correlation of applied force with BMI, suggesting that those with higher BMI values had a greater depth of soft tissue to deform and hence more compliant tissue. However, BMI did not correlate with bruise characteristics, so potentially an increased depth of soft tissue (be it muscular or adipose) at the impact site does not mean a larger bruise or a bruise of a certain appearance.

The physiological variables explored in this study appeared to have little or no relationship with the bruise, which may have been due to the narrow volunteer pool: the majority were young Caucasians who regularly took part in sporting activities. But it is more likely that there are other, more important, physiological confounding variables. Until these confounding variables are identified and their relationships understood, there must be serious questions over whether visually assessing bruising should ever be used within a medico-legal context.

The individual characteristics that were collected, although giving a profile of each participant, were basic in nature. Ideally, specific characterisation of the impacted thigh would have been carried out i.e. a measure of adiposity and we recommend that this and other potential confounding factors such as muscle and fat composition, should be measured at the impact site in any future study to ascertain their importance. Furthermore, during forensic investigations, there is no requirement for hair removal before images of bruising are taken, therefore we did not do so. Nevertheless, whilst this was a potential source of error, the presence of the hair itself would not have affected our colour and contrast results, presuming an equal distribution of leg hair in these areas, as the values reported were the difference between bruised and non-bruised areas and not absolute values. Another source of error was involved with the lassoing of the bruise areas. Whilst the same observer determined bruise size from all images, inter- and intra-observer variation in these measures was not ascertained.

The assessment of photographic technique was inconclusive in that there was no overall best technique, each having strengths and limitations. There was no conclusive way to reliably determine any pertinent information relative to bruise formation, or to create a reproducible colour model for bruise healing. For documenting bruising, CP imaging was found to give the clearest representation of the characteristics and development of bruising whilst minimising the effect of light reflection from the skin. IR photography did show strengths in the early stages of bruising as it could enhance the visibility of subcutaneous bleeding. Furthermore, measurements of bruise area for IR taken immediately after impact did provide an indication to the extent of bruising which would then be seen, yet the correlation was not strong enough to be used as a reliable predictor. As individual variability strongly influenced the results, there may be better alternatives to standard photography for identifying, documenting and interpreting bruising. Research should continue in other forms of imaging as to whether such imaging modalities provide enhanced and consistent information in addition to those included in this study.

Although experimental work has the advantage of accurately demonstrating how this type of injury varies for individuals, if it were supplemented with computer modelling, a detailed understanding of the localised tissue stress and strain could be achieved. When assessing individuality, future work should consider a more detailed approach to characterising individuals (e.g. measure adiposity rather than BMI), especially at the impact site, with a larger pool of volunteers. Combined with alternative documentation and interpretation methodology (e.g. ALS photography and automated bruise area measurements), a clearer understanding of bruise injuries could be achieved. Different anatomical locations should also be considered to not only continue to assess person-to-person variability, but also how bruising differs across the body. This approach should not only test different locations, but also measure skin tension for these locations. Only once a complete understanding of how all aspects of bruising are mechanistically linked together would ageing of bruise injuries become a reliable form of evidence within a forensic context: an understanding of the mechanisms involved should lead to a better understanding of the inter-subject variability and thus the limits of determining the age of a bruise.

Conclusion

This study collected data on aspects of bruise analysis including impact force, documentation techniques and visible bruise colour. Whilst CP and IR imaging methods demonstrated some advantages over standard colour photography, alternative imaging modalities should be investigated as to whether they provide more reliable quantitative bruise characteristics. With all photographic techniques, although general patterns in colour were observed, inter-subject variability meant that colour itself was not relatable to bruise age or to the level of force which caused the injury. Impact force, which must be strongly dependent on the mechanical behaviour of the impact site, was only partially influenced by BMI (R^2 = 0.321) and did not show any significant relationships with the resulting bruises' characteristics. Therefore, there must be additional physiological characteristics, not measured in this study, that are more important in explaining the variation in bruise appearance. Finally, as no two bruises appear the same under controlled infliction conditions, the processes of ageing a bruise, and estimating the force required to make that bruise, from the resulting bruise's appearance, are not reliable.

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Figure Captions

Figure 1: Correlation between BMI and peak force

Figure 2 Two three-day old bruises: (a) small bruise presenting mostly yellow tones (b) large bruise presenting with blue, purple and yellow tones

Figure 3 Bruise area as a function of day for individual bruises, measured from colour images

Figure 4 (a) ΔL^*, (b) Δa^* and (c) Δb^* variation with day for each bruise

Figure 5 Average contrast measured for different time periods for each photography technique

Tables

Photography technique	Average area (cm^2)		
	Impact mark	Surrounding red mark	Max bruise
Colour	3.31 ± 0.76	24.8 ± 9.75	20.8 ± 9.22
CP	3.05 ± 0.55	22.9 ± 10.0	21.0 ± 10.2
IR	8.51 ± 2.55	-	20.5 ± 9.96
IR (altered)	9.54 ± 3.39	-	21.1 ± 9.30

Table Captions

Table 1 Average area of the impact mark, surrounding red mark and max bruise (cm^2), for each imaging technique. Impact mark and surrounding red mark measured at Day 0, with max area being the largest area measured for each bruise, irrespective of day.

Figure 1

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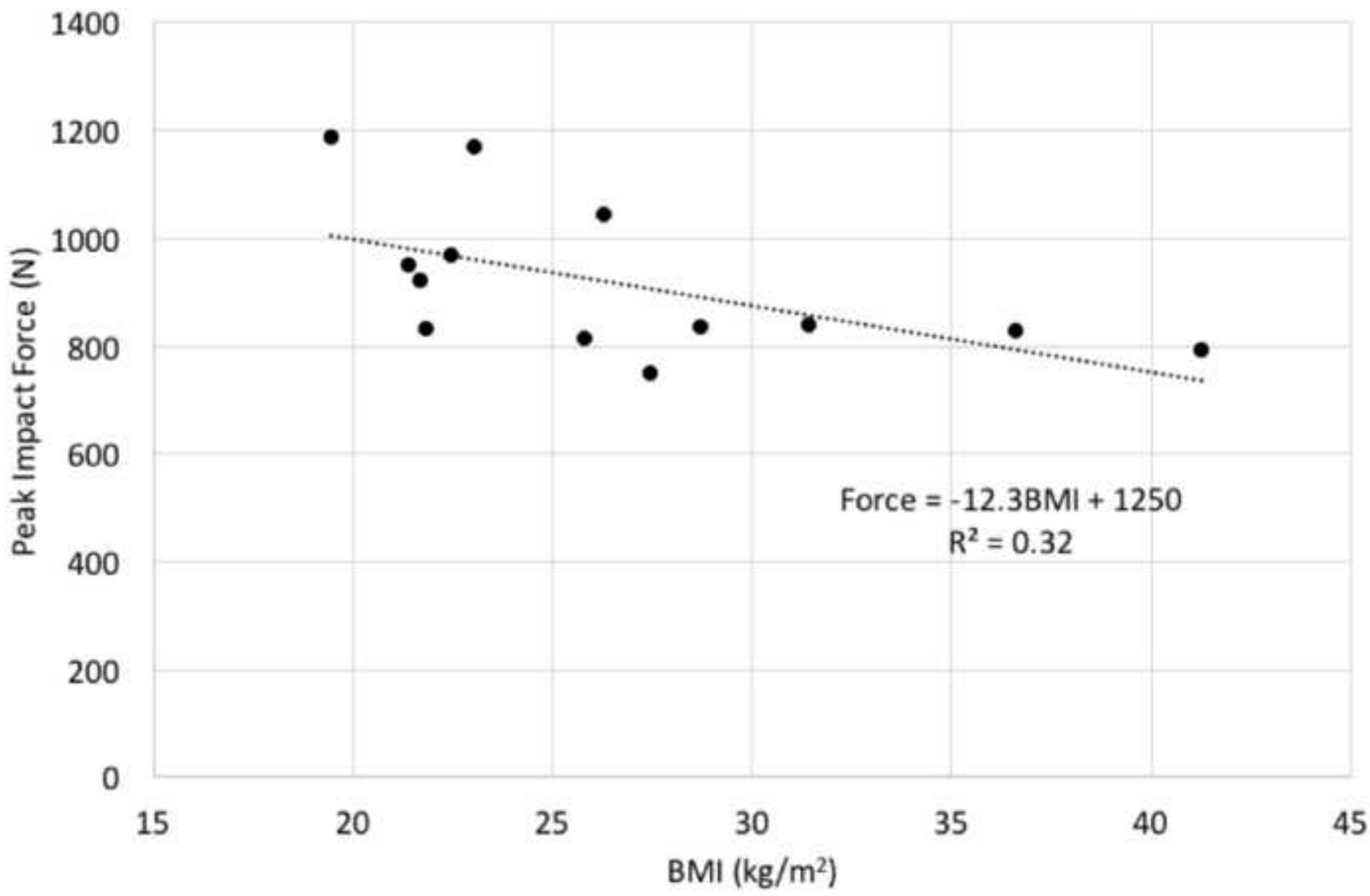

Figure 2
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Figure 3

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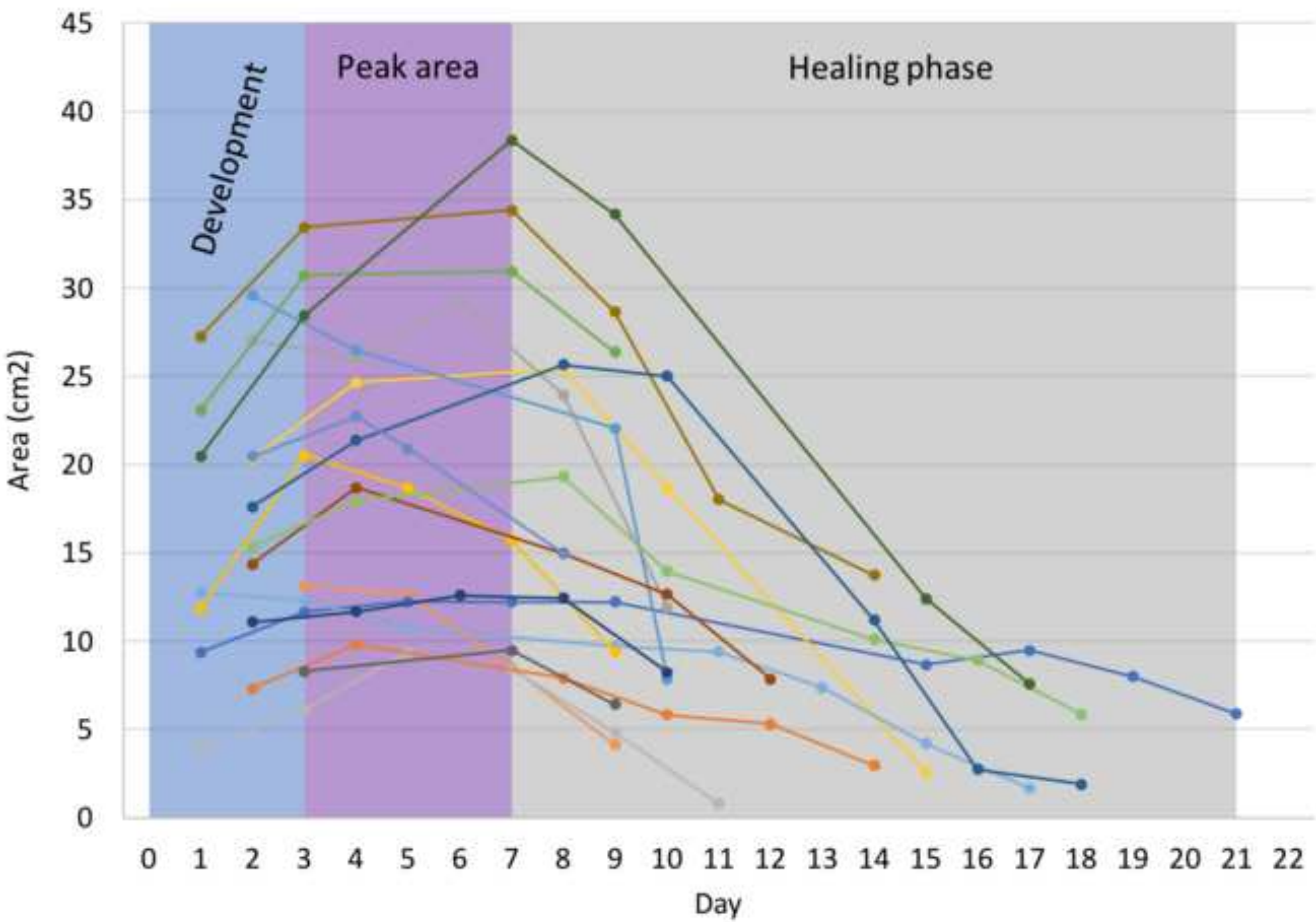

Figure 4a
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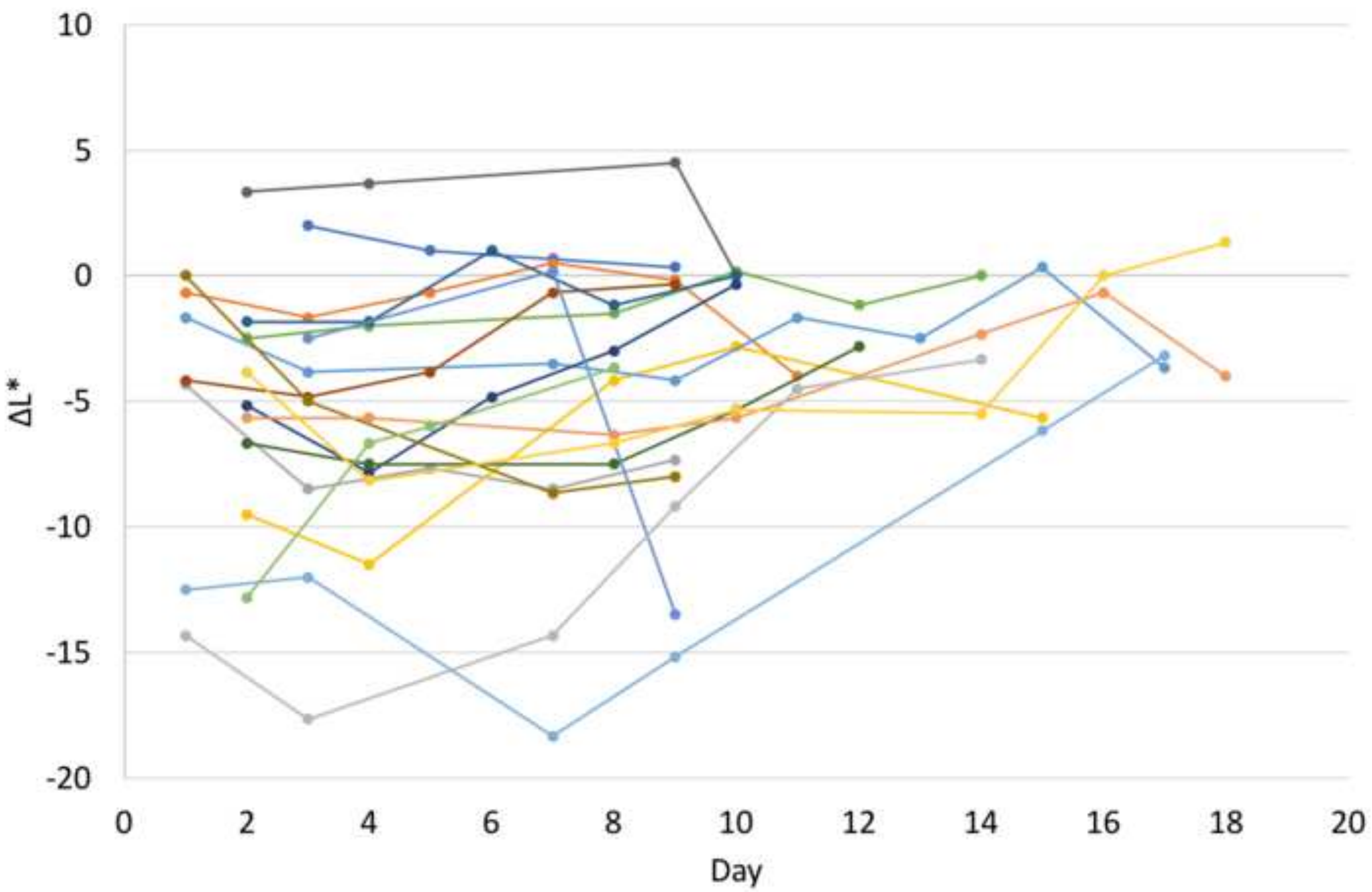

Figure 4b
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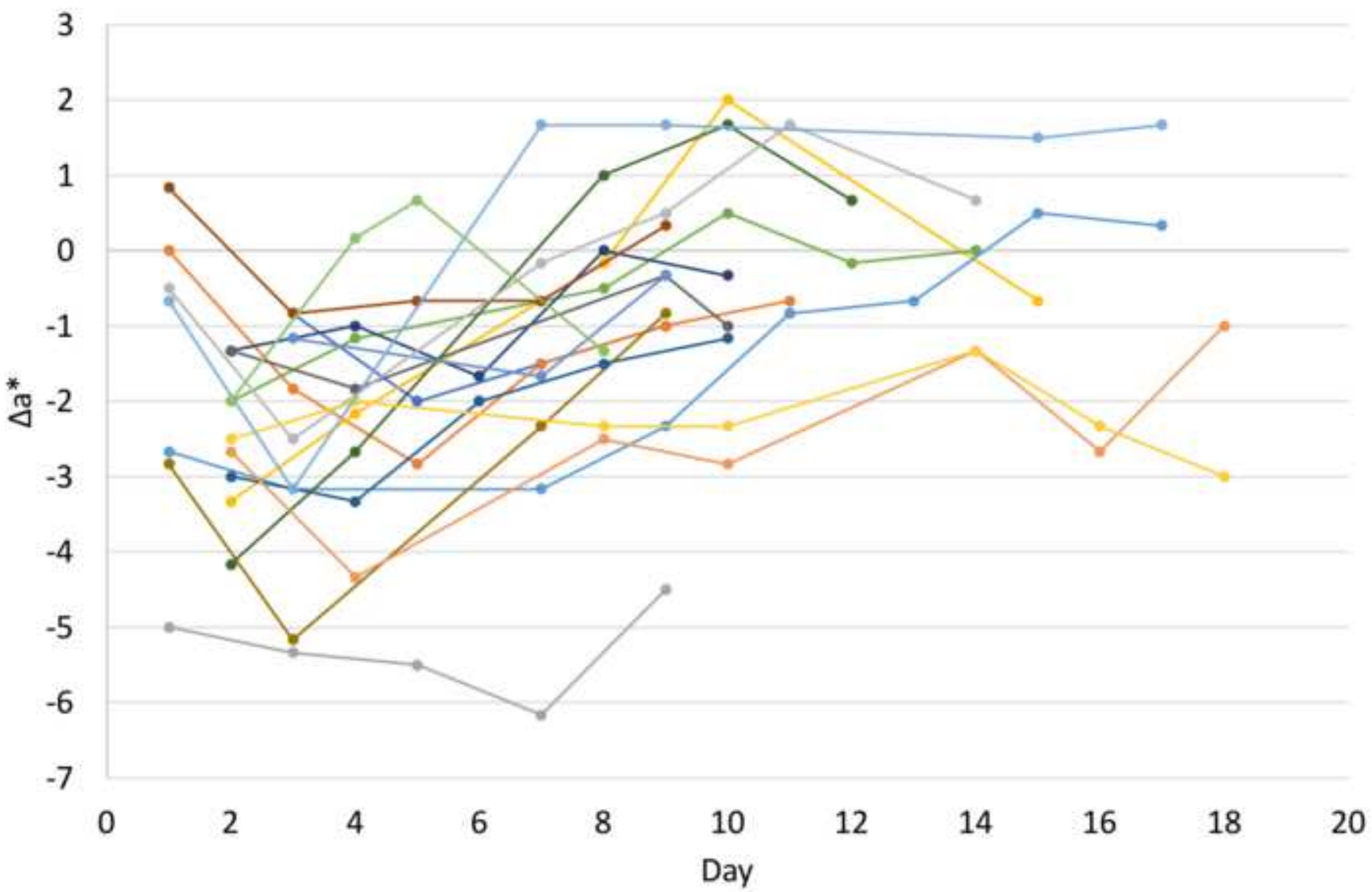

Figure 4c
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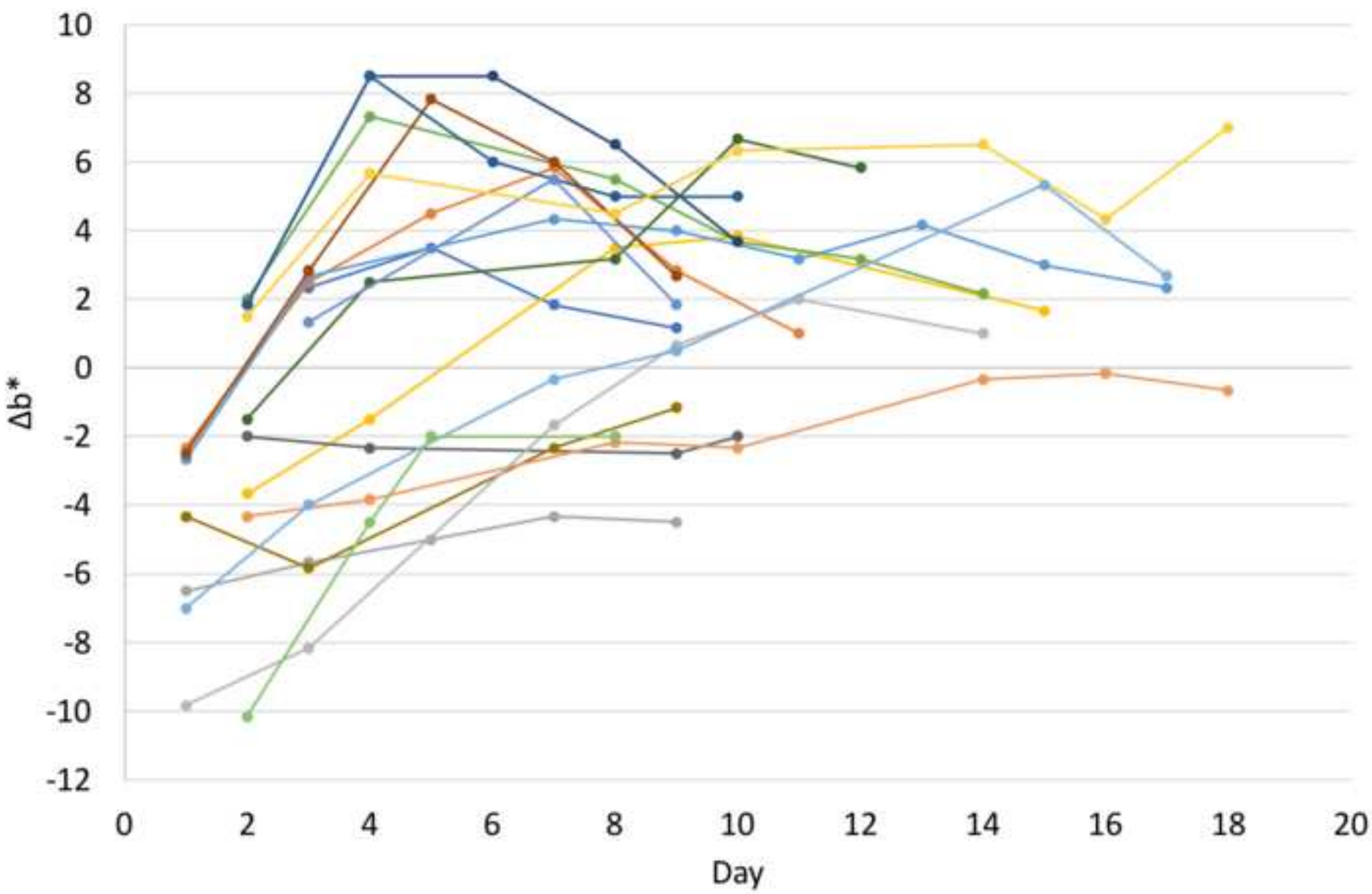

Figure 5

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